THE WEEK'S EVENTS

San Jacinto Tunnel Holed Through

Last barrier blasted from last of thirty-eight tunnels in the Colorado aqueduct line

San Jacinto tunnel on the Colorado River Aqueduct of the Metropolitan Water District of Southern California was holed through Nov. 19 at 10 a.m. Thirteen miles long, the San Jacinto tunnel is the last of the 38 tunnels, totaling 108 miles in length, which have had to be excavated on the aqueduct and on that part of the distribution system now being built. All other tunnels have been completed, and the entire 392-mile aqueduct is now 90 per cent complete.

Inflows of water under high pressure and unusually broken and heavy rock conditions have been met in construction of the San Jacinto tunnel ever since work got under way in December 1932. The tunnel was excavated from the west portal, from the Potrero and Cabazon shafts and from the Lawrence adit. The final barrier to be cleared away separated the Lawrence adit bore and the Potrero shaft bore. A full description of the work is given on p. 669 of this issue.

With holing through of the San Jacinto, a clear passageway is now open along the aqueduct all the way from the Colorado River to the Cajalco reservoir. Six miles of the San Jacinto tunnel remain to be lined. The entire aqueduct system is scheduled to go into operation by the middle of 1939 delivering water to 13 coastal cities.

Wide World Photo

Miners from the Lawrence adit and Potrero shaft bores of the San Jacinto tunnel meet as the last barrier wall is blasted away. Two miners stand above the crowd at the spot where the last rock wall was removed.

Political Shake-up In Ohio Road Body

Repercussions of Democratic primaries result in resignation of fourteen officials

Ohio highway director John J. Jaster, Jr. and his assistant, G. Murray Anderson, have resigned in anticipation, it is understood, of the change in the state administration which will take place in January, when Governor-elect John W. Bricker, Republican, will displace Governor Martin L. Davey, Democrat.

Shortly afterward, nine division engineers in the engineering division of the highway department, tendered their resignations. Governor Davey announced that he had informed the nine men that they could either resign or be fired. He said he took this action because the engineers had given affidavits to Charles Sawyer, Democratic candidate for governor, that Davey had entered into a patronage agreement with the Republican candidate. To succeed Jaster, the Governor appointed Ivan R. Ault, chief of the division of maintenance, as acting director of highways and Xenophone G. Hassenplug as assistant. Ault is now under indictment in Knox county on charges of soliciting primary campaign funds for Governor Davey from civil service employees. His trial has been set for Dec. 5.

Men affected

The division engineers who resigned are: C. A. Smith, Lima; F. W. Stopher, Toledo; P. K. Troutman, Newark; Frank W. Turner, Delaware; H. C. Miller, Sidney; Walter E. Willard, Middletown; Joseph N. Doyle, Chillicothe; Harley E. Calvin, Marietta; and Lewis L. Drasler, Cleveland.

To replace these men Ault has appointed the following: Lowell Schaueblin, Lima; Kenneth Terry, Toledo; Lyle McBride, Ravenna; H. P. Mason, Newark; J. M. Morrissey, Delaware; Oscar Schilling, Sidney; J. W. Reppel, Chillicothe; G. M. Gerhart, Marietta; and Ted Kauer, Cleveland. These appointments were announced by the new highway director on Nov. 15.

Contractors Look Into Public Relations

Publicity, legislation, and WPA discussed at A.G.C. fall board meeting at Excelsior Springs

A tendency toward positive rather than the customary negative action on important contracting questions was shown by the Associated General Contractors at their fall board meeting held at Excelsior Springs, Mo., Nov. 14–16. An aggressive attitude was adopted toward such problems as legislation affecting contractors and the construction business, labor relations, public and industrial relations, and, of course, WPA, the contractors' chief worry. In just one year the association has changed from abject horror of the word "labor" to a frank realization that labor relations are an integral part of construction procedure.

Probably more important was the determination of the association to outline and even initiate legislation that affects contractors and their business. Heretofore the A.G.C. legislative program has been largely one of fighting undesirable and harmful proposals. Now the legislative committee is empowered to work out a program of constructive and desirable proposals. This action is timed to inform both old and new members of the coming Congress as to the wishes of the contracting branch of the construction industry.

Publicizing contractors

Public and industrial relations were subjects of discussion in an A.G.C. meeting for the first time. Dan Kimball, of Michigan, pointed out ways and means of publicizing contractors and their work through advertising, newspaper accounts, lectures, radio talks, and at-the-site courtesies to the inquisitive and interested general public. Lack of display of the firm's name and A.G.C. seal on construction projects was cited as an example of the contractors' disregard of publicity. The group quickly sensed that public relations include industrial and employee relations as well.

Subcontract practices

Discussion of subcontracting relations revealed that the subs are engaging in practices considered detrimental to the interests of construction as a whole and general contracting in particular. Local A.G.C. chapters were urged to meet with local subcontracting groups in an effort to iron out differences of opinion and misunderstandings and to formulate practices beneficial to both parties.

In regard to relations with engineers and awarding authorities, discussion turned to betterment of specifications and contract requirements, especially by the elimination of unfair and impossible stipulations. Prequalification of contractors was considered, this discussion being led by H. K. Bishop and J. L. Harrison of the Bureau of Public Roads, who pointed out that prequalification sought a balance between contract defaults and restricted bidding.

E. J. Harding, managing director of the A.G.C., presented a long report of the association's program and activities. One of the highlights of the report was the revelation that labor relations were becoming so important that the present facilities for handling them in the national office are inadequate. Some means must be found, he said, to enlarge and finance the services demanded by the membership regarding labor matters. E. P. Palmer, president, also discussed association affairs. He remarked about the liberal attitude taken by the A.G.C. today on questions formerly regarded as too hot to handle.

WPA jobs

No A.G.C. meeting would be complete without a sounding off on WPA. This time the attitude expressed was still belligerant, but a note of conciliation was detected in the consideration of WPA-contract projects. The national staff was authorized to collect and disseminate information concerning the operation of these projects for the benefit of interested chapters and members. This might be regarded as a break in the contractor-WPA battle, but the secondary lines were strengthened by a strong declaration that WPA must be liquidated as soon as possible.

Discussion of the Fair Labor Standards Act (wages and hours) left the session in doubt as to the application and effect of the law in construction. It was pointed out that the administrator lacks the power to include or exempt any industry from application of the act, except those mentioned specifically, and the courts alone can determine the exemption or inclusion of any specific industry. Therefore, contractors were advised to follow rules and regulations handed down in other industries. Meanwhile, court decisions will be awaited, and, if they are found intolerable to construction, attempts will be made to have the law revised.

Merit and debit ratings

The A.G.C. will endeavor to have postponed the application of the merit and debit rating on the unemployment tax. Contractors, it was pointed out, have no control over the intermittent and seasonal employment in the industry, and therefore should not be penalized by the inevitable debit rating.

Plans were announced for the coming annual convention to be held in San Francisco March 5–11, in connection with the construction equipment show and meeting of the American Road Builders Association. Manager Floyd Booe of the Northern California Chapter promises that the convention will be the greatest in A.G.C. history and a fitting occasion to celebrate the

WINDOWLESS FACTORY TO OPEN IN OHIO

OPERATIONS will begin next week in Industrial Rayon Corp.'s $11,500,000 air-conditioned windowless plant at Painesville, Ohio. Daylight enters this 14-acre plant through wall panels and monitors of glass block, 371,000 of which have been used in the factory, the laboratory, the power house and auxiliary structures, the largest glass block installation on record. Engineered by Wilbur Watson & Associates and built by the Hunkin-Conkey Const. Co., both of Cleveland, the buildings include a 15-m.g.d. water plant.

twentieth anniversary of the founding of the association.

About 100 contractors, chapter managers and secretaries, and national staff members attended the three-day session. Guy F. Atkinson of San Francisco, present vice-president at large, was nominated as president for 1939. H. B. "Pat" Zachry, Laredo, Tex., was nominated for vice-president at large.

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High Wind in Wyoming Blows Down Brick Wall

A gale which reached a maximum wind velocity of 66 miles per hour at Cheyenne, Wyo. blew in the side of a brick hangar at the Cheyenne airport Nov. 15.

The wall which blew in was entirely blank except for a small wooden door at one end. The wall was composed of a row of 4-in facing brick separated by an air space from an inner row of 6 in. hollow clay tile. Three brick projections were built out from the wall about 8 in. Practically the entire side of the building was blown inward, wrecking several planes inside and causing considerable other damage.

The hangar was owned and operated by the Cheyenne Flying Service of that city.

CONTRACTS AND CAPITAL

ENGINEERING construction awards for the short week due to the Thanksgiving Day holiday total $49,970,000, a decrease of 31 per cent from the volume for the corresponding 1937 week.

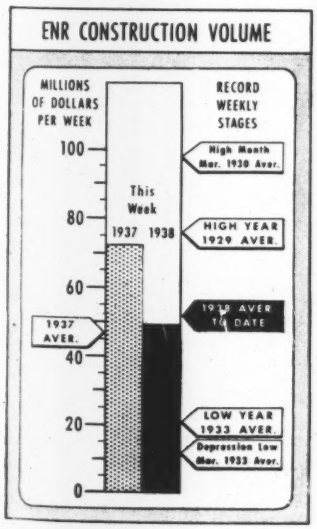
Cumulative construction total for the 47 weeks of 1938, $2,452,681,000 is 9.6 per cent above the $2,238,590,000 volume for the corresponding period a year ago, and is 0.6 per cent above the construction total for the entire year of 1937.

Public and private awards for the week are 29 and 37 per cent lower, respectively, than for the week a year ago.

In the classified construction groups, sewerage, commercial building and large-scale housing, public buildings, earthwork and drainage, and streets and roads are above their respective totals for the 1937 week. Sewerage and commercial building and large-scale housing report gains over a week ago.

New capital for construction purposes for the week, $46,744,000, is 228 per cent above the week last year. It is made up of $35,759,000 in state and municipal bonds, $8,135,000 in PWA allotments for non-federal projects, and $2,850,000 in corporate security issues.

New construction financing for the year to date totals $3,560,046,000, an increase of 69 per cent over the $2,110,362,000 reported for the 47-week period last week.



CONTRACTS

(Thousands of dollars)

	Week Ending Nov. 25 1937	Nov. 17 1938	Nov. 24 1938
Federal	$977	$11,075	$3,945
State & Municipal	51,624	37,510	33,436
Total public	$52,601	$48,585	$37,381
Total private	19,880	10,195	12,589
TOTALS	$72,481	$58,780	$49,970
Cumulative 1938 (47 weeks)			$2,452,681
Cumulative 1937 (47 weeks)			$2,238,590

Note: Minimum size projects included are: Waterworks and waterways projects, $15,000; other public works, $25,000; industrial buildings, $40,000; other buildings, $150,000.

NEW PRODUCTIVE CAPITAL

	Cumulative 1937 47 Wk.	1938 47 Wk.
NON-FEDERAL	$1,364,139	$2,416,351
Corporate securities	499,951	353,782
State & Mun. bonds	456,123	594,856
PWA loans, grants	178,126	833,320
RFC loans	29,939	100,344
U.S.H.A. loans	.....	265,054
R.E.A. loans	.....	67,495
Federal Aid-highways	200,000	201,500
FEDERAL	$746,223	$1,143,695
TOTAL CAPITAL	$2,110,362	$3,560,046

FHA MORTGAGES

	Week Ending Nov. 18 1937	Nov. 12 1938	Nov. 19 1938
Selected for appraisal	$9,887	$16,380	$20,529*
Cumulative 1938 (46 weeks)			$901,106*
Cumulative 1937 (46 weeks)			$546,763

* Subject to revision.

ENR INDEX NUMBERS

Index Base		1913	1926
Construction Cost	Nov.	234.40	112.69
Building Cost	Nov.	195.58	105.71
Volume	Oct.	217	95

Three States Halt Gas Tax Diversion

California, Michigan, and New Hampshire approve constitutional amendment on diversion

Voters in California, according to incomplete but apparently conclusive returns from the November election, decisively approved a constitutional amendment requiring that revenues from gasoline taxes be used exclusively for highway purposes. As of Nov. 15, the tabulation showed 1,305,000 for the amendment and 693,000 against.

In Michigan likewise an anti-diversion amendment was adopted by a large majority.

New Hampshire voted 96,600 to 23,800 in favor of a similar amendment.

By a very close vote, Alabama voters defeated an amendment which would have reserved highway tax revenues for highway purposes. The official count on the vote is 54,500 in favor and 59,800 against.

Also defeated was a California measure which would have established a highway commission of five members controlling all phases of highway operation, construction and regulation. The vote was 843,000 in favor and 1,200,000 against, as tabulated on Nov. 15. California highways are now under the control of a division of the Department of Public Works.

Other measures

Measures of engineering interest which were passed on by the voters Nov. 8 additional to those reported last week (*ENR*, Nov. 17, 1938, p. 603) include the following: In Arkansas, a constitutional amendment was defeated which would have obligated the major portion of the state motor vehicle and gas taxes for payment of principal and interest on outstanding highway bonds. In Missouri, amendments were defeated which would have increased the state gas tax to 3 cents and would have set up a 10-year road building program. In Rhode Island, measures were defeated which would have authorized a bond issue of $27,000,000 for hurricane rehabilitation, including $5,000,000 for roads and $5,000,000 for bridges.

Also defeated was an Arkansas measure providing for payment by the state of the obligations of bridge improvement districts and of municipal improvement districts. In Louisiana, an amendment was approved which authorized a bond issue up to $5,000,000 for construction of farm-to-market roads and maintenance of state highways and bridges.

Green Mountain Dam Contract Let

Chicago company bids $4,226,000 for first part of Colorado-Big Thompson project to get going

The first contract for construction work on the Colorado-Big Thompson project in Colorado was awarded Nov. 16 to the Warner Construction Co. of Chicago on its bid of $4,226,000. The contract covers the building of the Green Mountain Dam and the Green Mountain power plant, both located on the Blue River about 16 miles southeast of Kremmling, Colo.

The dam and power house are two of the principal features of the Colorado-Big Thompson project. This project will bring surplus water from the headwaters of the Colorado River on the western slope of the Continental Divide to supply supplemental water for land on the arid eastern slope in northeastern Colorado. The Green Mountain dam is constructed to provide replacement storage and thus protect water users in the Colorado basin.

The Green Mountain dam will be 270 ft. high with a crest length of about 1,300 ft. and a top width of 35 ft. It will be an earth and rock fill structure and will be exceeded in size and height, in its class, only by San Gabriel dam No. 1 in California. The power plant will be located on the right bank of the river downstream from the dam. Of reinforced concrete construction, it will house two main generating units of 12,000 kw. capacity. Other important elements of the project include a 13.1 mile tunnel under the Continental Divide, and the Granby reservoir in which the water actually diverted will be stored. Willow Creek Canal will bring water from Willow Creek, a tributary of the Colorado River, into Granby reservoir.

Shadow Mountain Lake, formed by construction of the north fork diversion dam near the junction of the Grand Lake outlet and the Colorado River, will reduce the length of the tunnel. In addition to the Green Mountain power plant, five more will be installed as the power market opens up.

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Expansion Program Planned For Cornell Engineering

A $6,000,000 program to expand the buildings and faculty of the Cornell College of Engineering was announced Nov. 17 by President E. E. Day of the University. A committee of trustees, he said, had recommended an increase of $2,500,000 in the endowment of the college to support special professorships and to raise the general level of faculty salaries. The committee also recommended that $3,500,000 be spent for construction and equipment of two new buildings, one as a college of chemical engineering and the other a materials and metallurgy laboratory.

Bureau of Reclamation Photo

SITE at which the Green Mountain Dam will be built on the Blue River in Colorado. The reservoir created by the dam will contain 152,000 acre-ft. of water and will cover 2,100 acres of land.

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New York to Tear Down Sixth Avenue El

New York City officials expect to begin demolition work on the 60-year old Sixth Avenue elevated line in Manhattan some time next month. The City Board of Estimate voted formal condemnation of the line Nov. 16. It was decided that half the cost of condemnation would be assessed on nearby property and the other half would be paid by the borough of Manhattan.

A committee of bondholders of the Manhattan Railway Co., former owner of the line, recently purchased the line at a foreclosure sale for $12,500,000. The city is expected to purchase the line for about this amount, but $9,000,000 of the purchase price will be credited against back taxes due the city.

Built in 1879, the Sixth Ave. line runs from Morris St. in lower Manhattan, partly along Sixth Ave., to 53rd St. and 9th Ave. where it joins the 9th Ave. elevated line.

A section of the New York City municipal subway system is now under construction along Sixth Ave. between 8th St. and 53rd St. Considerable work had to be done underpinning the El in the open cut sections of the subway.

More WPA-Contract Jobs Scheduled for Texas

The Works Progress Administration of Texas and the Associated General Contractors chapters in the state have worked out a plan to furnish WPA labor on regular contract projects that has proved so successful in two test cases that the plan will be extended at once. A sewer project in Dallas and a state highway job were selected for the trial.

All WPA does is furnish common labor on projects approved by it which have been let by contract in regular manner by the awarding officials of the state or city. The awarding agency provides the plans and engineering services and calls for bids in the usual manner. WPA furnishes and pays for the common labor only, as called for by the contractor, and also supplies materials up to $7 per man-month of common labor. Labor to be furnished by the WPA and all materials to be supplied are noted in specifications.

All control of the operations is under the awarding authority and the contractor, for WPA has nothing to do with the planning, design or construction, except that it requires safety measures to be carried out on the job, specifying the A.G.C. Safety Manual as a guide. The contractor may fire any undesirable workman. All materials other than those specified as supplied by WPA, all operators and skilled labor, all supervision and clerical forces are supplied by the contractor.

Hurlburt Jacoby Dies, Ohio Research Man

Remington, former New York contractor, dies at seventy-seven in Cazenovia

Hurlburt S. Jacoby, director of industrial research and field director of the engineering experiment station at Ohio State University, died in Columbus, Nov. 17, at the age of 52. He had held this position since 1934. Since his graduation from Cornell University in civil engineering in 1910, Jacoby had served as a professor of structural engineering at Pennsylvania State College, as engineer for the McClintic-Marshall Co., as chief engineer for Standard Steel Construction Co., as district engineer for the Austin Co., and as secretary and chief engineer of the H. K. Ferguson Co.

His interest in both university and engineering work was inherited, for his father was Henry S. Jacoby, professor of civil engineering at Cornell, and author of well-known "Roofs and Bridges."

ELIPHALET REMINGTON, retired engineer and builder, died in Cazenovia, N. Y., Nov. 13 at the age of 77. He attended the School of Mines at Columbia University and then went into the building trade. In 1895, Remington went to British Columbia to supervise the construction of a dredge for gold mining. Later he was general superintendent of the Fuller Construction Co., in New York, and during the war he served with the Foundation Co., New York, on wartime building of ships of many types.

JAMES N. HATCH, PWA engineer examiner of Alameda, Calif., and for many years power plant consulting engineer in Chicago, died Nov. 11. Born 70 years ago in St. Helena, Calif., he was graduated from the University of Michigan in 1892 and gained his early experience in shipyards and railroads, and with the Carnegie Steel Co. From 1903 to 1914 he was structural engineer with Sargent & Lundy, after which he went into private practice in Chicago, Pasadena and Alameda. Under the *nom de plume* of Truthful James he wrote poems of the engineer and his experiences.

HERMAN BERGHOLTZ, engineer, and Mayor of Ithaca from 1930-1934, died there Nov. 16 at the age of 74. Under Bergholtz's direction, Ithaca's first traction system was built. He also organized the city's electric light company. By profession a consulting engineer, he was identified with civic improvements, and was one of the sponsors of early public utilities in Ithaca. A native of Vernamo, Sweden, he attended private schools there, and matriculated at technical institutes in Germany.

JOHN A. BRYANT, treasurer of Bryant & Detwiler Co., contractors on many large buildings in Detroit, died there Nov. 15 at the age of 58. He was graduated from the University of Michigan and came to Detroit in 1902.

CHARLES K. HEEBNER, 55, construction manager of United Engineers and Constructors, Inc., died in Philadelphia, Nov. 14.

WILLIAM E. MOORE, retired building contractor of Charlestown, W. Va., died there Nov. 17 at the age of 68.

LAWRENCE D. BARLEY, 37, who for many years was secretary-treasurer of the Wilson Engineering & Contracting Co., died Nov. 10 in Xenia, Ohio.

ETIENNE PELLAND, town engineer, of Rouyn, Quebec, died in a fire which destroyed a city block there Nov. 12.

HENRY M. COOPER, 57, sales representative of Sauerman Bros. in the New York area, died in Port Washington, L. I., Nov. 16.

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Legislative Platform Adopted by A.A.A.

Ending their four-day convention at Cleveland on Nov. 19, the American Automobile Association adopted a 16-plank platform of measures to be pushed by its 750 affiliated clubs during the coming year.

The automobilists went on record in favor of: Regulation of trucks in the interests of safety, including week-end restriction. Enforcement of health regulations in roadside eating establishments. A strict salary basis for enforcement officers, to eliminate speed traps. Sound enforcement of traffic regulations. Reduction of hazards to pedestrians. Fair trade practices in the auto industry. Development of off-street parking facilities in central business districts. Frequent inspection of headlights. And safety regulations for bicycles.

Opposed by the Automobile Association were the following: Politics as an influence in road building programs. The proposed $12,000,000,000 transcontinental superhighway system. Requirement of permits to cross state lines. Federal control of drivers or private passenger car traffic. Illuminated advertising signs interfering with stop and go signals. Animals on highways.

LABOR NOTES

NEGOTIATIONS for a labor agreement in the heavy construction industry in the State of Washington will be carried on with contractors on a statewide basis by the Washington State Building Trades Council, the council has announced. The building trades unions have authorized the executive board to enter into contracts. Previously, separate contracts were in force in the eastern and western parts of the state.

A SHORTAGE of plasterers in Juneau, Alaska, made it necessary for Gust Lauch & Sons of Seattle to bring in six plasterers by air to finish the interior of a $500,000 hotel being built by A. W. Quist Co. of Seattle.

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Cooper Union Studies Liberalized Training

As the initial step in an educational program designed to foster social responsibility among engineers, Cooper Union has completed the compilation of a bibliography on "The Non-Technical Aspects of Engineering Education." It is believed to be the first such compilation on this subject.

The new bibliography is intended, according to Cooper Union director Edwin F. Burdell, to aid "the engineering faculty to keep abreast of what changes have been made in various schools as well as of what leading educators and professional people think about the necessity of modification of the conventional and crowded technical courses of study." Burdell looks to the Cooper Union faculty, he said, to develop the needed standards of engineering acumen.

'My approach," Burdell said, "was to put into the hands of Cooper Union faculty the evidence that such improvements are necessary. . . It is my exuectation that once the engineering faculty has investigated contemporary thought along this line, the faculty members will see fit to take steps not only to maintain existing standards but perhaps to set standards and objectives to which other schools may aspire."

The new policy is described by Cooper Union authorities as a "constructive response" to the recommendation made in President Roosevelt's letter of October 1936 to heads of schools and colleges throughout the country. In that letter the President asked that engineering courses be so balanced "as to give coming generations of engineers the vision and flexible technical equipment necessary to meet the full range of engineering responsibilities."

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NOVEMBER 24, 1938

FOR THE FIRST TIME in six years there is peace and quiet along the Colorado Aqueduct, for San Jacinto was holed through last week. Desert landscapes whose charm has somehow seemed overemphasized in comparison with the reality of barren hills and dunes can now be appreciated. The dramatic quality of color-splashed sunsets, red-blooming ocatillas, and sentinel sajuaros silhouetted against the background of greasewood and smoke-tree scrub, can now be considered important. With San Jacinto tunnel open the great aqueduct is as good as finished. Climaxing one of the most difficult construction jobs in history, this 13-mile tunnel presented tunneling at its worst, requiring every resource of knowledge, ability and ingenuity that could be mustered by construction worker and engineer to overcome its bad rock and water. In less degree other difficulties were met and overcome elsewhere along the 240-mile line. This issue, written by the men in responsible charge of this great undertaking, brings these difficulties and their solutions back to life. It contains lessons and inspiration for construction men everywhere. For few there are who have not found, when they came up out of a spirit-breaking San Jacinto or its equivalent, that landscapes are still beautiful and that the world is in need of more facilities that none but they can provide.

Construction Supreme

THE RECORD presented in this issue is that of an undertaking without peer in the history of construction—for conception, for plan and for execution. Only the boldest imagination could dream of lifting a river over more than a quarter-mile of mountain height and carrying it across two hundred miles of desert. Only the highest financial courage could command the huge sums to make such a dream come true. Engineering difficulties match those of conception and finance, but all were faced and met, in the designing office. The incentive that inspired the dream and its realization was knowledge that the Colorado's water was the last that ever could be obtained to supply the southern California slopes. The work is an enduring monument to every man who had part in it, from William Mulholland to the last man leaving San Jacinto.

One Way Out

THE OLD POLITICAL RULE "If you can't lick 'em, join 'em" might apply in the fight contractors are waging to get WPA out of the construction business. Contractors have viewed with just concern the growth of WPA in construction, far beyond its original intention of dealing only with small projects offering a maximum of hand labor employment; they have seen a considerable part of their legitimate market taken over in the sacred name of relief. Protestations and bitter resolutions have been of little avail. WPA is here, it has huge sums to spend, it is pledged to supply employment for millions, and it seems determined to do most of this through construction. Recognizing these hard facts, a few groups of contractors have sought to cooperate with WPA rather than fight it. The plan worked out by the WPA and the Associated General Contractors in Texas seems to be the best yet tried. Here WPA is relegated to the role of labor agent, stepping out of contracting, supplying and paying common labor only on regular construction projects awarded in customary fashion by public agencies. Altogether the plan seems the most logical yet offered for WPA construction with least disruption of the industry.

Public Relations

A MILD SENSATION has been caused in New York City by the simple expedient of acknowledging the fact that everyone is interested in a construction job. The acknowledgment takes the form of a roofed-over gap in the construction fence around the excavation for a new building in the Rockefeller Center group. In a moment of inspiration, someone thought of naming this kibitzers' platform the "Sidewalk Superintendents' Club," from which point it was easy to go on and issue "membership" cards and to devise a coat of arms; the possibilities are limitless once one enters into the spirit of the thing. And the payoff is in the fine response from the public in goodwill, to say nothing of the publicity that the job gets. In the announcement that was made by Rockefeller Center, Inc., it is not clear how much George J. Atwell, the foundation contractor, or Hegeman-Harris Co., the general contractor, had to do with the scheme. We hope they thought of it, for it is one of the best examples of a public relations attempt on record. The Austin Co. on its National Broadcasting Co. job in Hollywood provided similar opportunity for the public to view its operations with a comparable development of good will. The lesson to be learned is

that better public relations is not always—or even usually—a complicated, difficult or troublesome matter. A simple facility such as a larger hole in the fence, presented with a slight sprinkle of showmanship, is a good start on the road to gaining public confidence.

Logical Highway Planning

THE FIRST PLANK in the platform of the American Automobile Association will find universal support among those interested in sound development of our highway system. It reads: "Eliminate politics as an influence in roadbuilding programs. Let engineering surveys and sound economics dictate the programs." This demand is particularly pertinent at this time when the nation-wide survey of roads and road traffic is approaching the point of applying its results to comprehensive highway planning. Heretofore even the best planning has been based in large part on guesswork or on limited studies of a particularly bad local situation; usually the possible effect of a proposed change on connecting routes was not known, and often it was not even considered. The survey data will enable the effect of any highway change to be more definitely determined. The time, therefore, is opportune for the emphasis that the A.A.A. has given to the need for basing all our highway planning on fact and for discarding motive.

Arbiter or Advocate

WHEN TIME-HONORED PRACTICES are challenged by new conditions it is imperative that the soundness of the old practices be reexamined. So the traditional relation between engineer and contractor, which is tending to change under pressure of modern requirements, needs renewed study. The position of the engineer as impartial arbiter between the owner, who is his employer, and the contractor is in danger of being transformed into one of sole responsibility to the employer. This trend deserves thorough consideration.

In the days when construction was handled largely by the retained consulting engineer it was axiomatic that the engineer in directing the work served as arbiter between owner and contractor. Today most construction projects are directed by engineers continuously employed by the owner, and some engineers believe that under this condition their responsibility is to the owner alone.

Under the older view the engineer, although paid by the owner, was rigidly fair to both sides in interpreting and applying the contract. His judicial function of deciding on the respective rights of the contracting parties was acknowledged by law books and insisted on by courts. Indeed the sole ground for upholding the large powers given to him by the customary contract terms—that quantities or facts shall be accepted "as determined by the engineer" and that "the engineer's decision shall be final"—was that the judicial attitude of the engineer made the contract a truly reciprocal agreement.

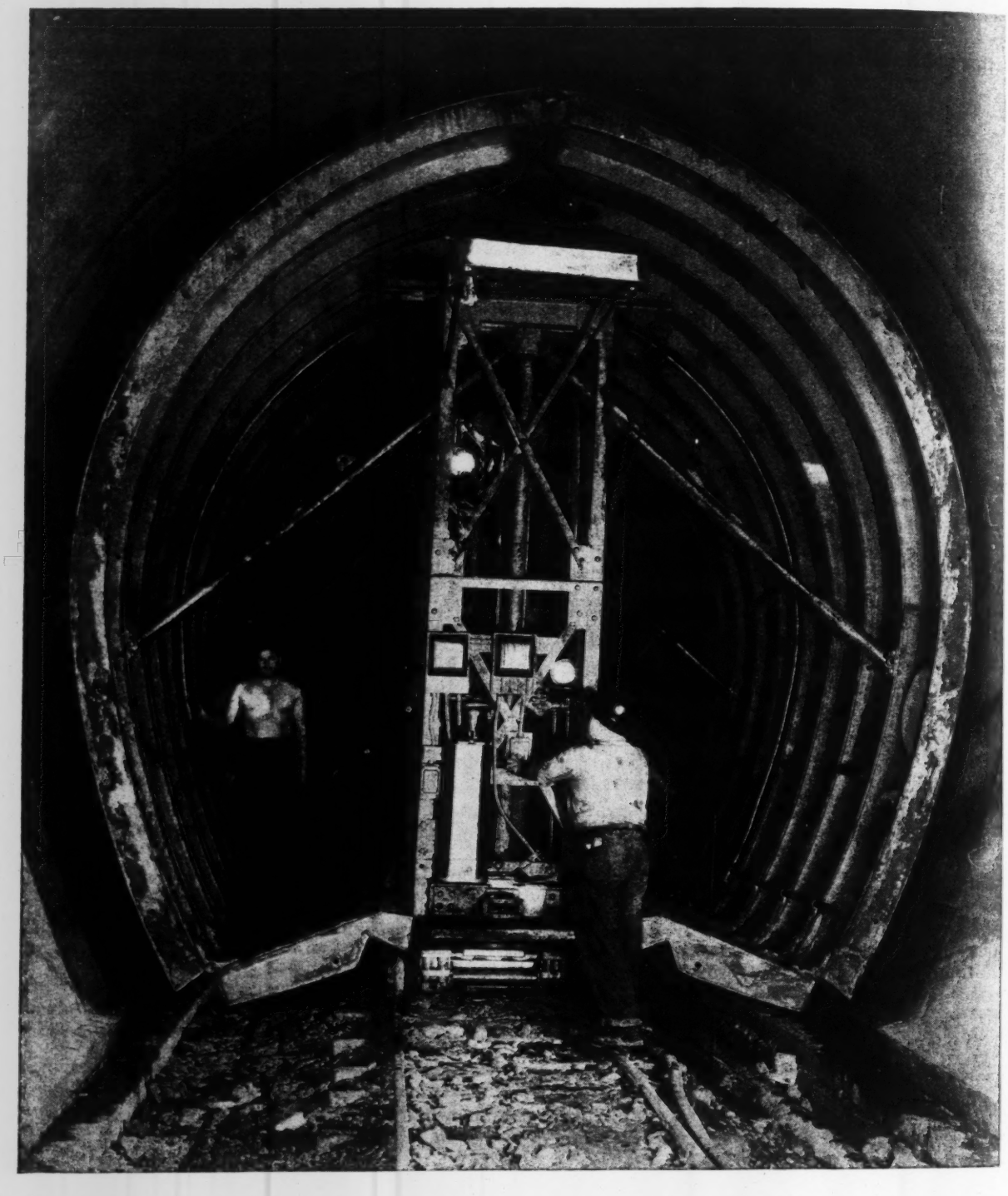
Under the newer view, if it can be called such, this whole relationship is altered. One inevitable effect may be deduced from past experience: In many noteworthy contract disputes proof was brought that the engineer had not judged impartially, and in every such dispute the contractor won his claim. Courts have uniformly held that the engineer who favored his employer was recreant to his trust and have overthrown the engineers' decision regardless of contract terms.

It is of the very essence of construction contracts as customarily written that the powers vested in the owner's engineer will be exercised without favoring the owner's interests. If this be admitted, it follows that the employed engineer administering a contract is in the same position as the retained independent engineer. By the nature of the contract terms he is an arbiter; and if he insists that he is his employer's advocate instead, the fundamental tenets of contract practice will have to be discarded.

What new contract terms would be necessary to accord with the advocate theory of the engineer's function is less obvious. Some provision would have to be made for deciding the numerous questions of contract obligations that arise in the course of even the simplest work. With the engineer committed to a partisan position, another person or agency would have to be provided to make these decisions, and this new person would become the de facto engineer of the work.

To draft a contract requiring no technical supervision of its execution is well beyond the range of possibility. If therefore the engineer elects to abdicate his function here, and allows another party to become the actual engineering authority in the field, the long-established system of contract construction would be greatly weakened, if not destroyed. And probably force-account construction would be in little better shape, since the engineer who is unwilling to be fair to the contractor is no more likely to be fair to job, to workmen and to all others concerned.

In short if the view that the engineer is the owner's representative and advocate be applied to the requirements of practice it will be seen to be untenable. The engineer can no more divest himself of responsibility for fair and equitable administration of a contract placed in his charge than he can evade responsibility for safe design.



Steel forms for lining the 16-ft. tunnels were designed for ease and speed in setting and in releasing for movement to a new position.

The Colorado River Aqueduct

Unprecedented project to bring water to the Los Angeles region from the Colorado River made practical by skillful engineering and able construction management

THE COLORADO RIVER AQUEDUCT now nearing completion will bring 1,600 sec.-ft. of water (one billion gallons per day) across desolate desert wastes and through rugged mountain ranges to the coastal plain of Southern California. An unprecedented and formidable undertaking in nature, the project at first seemed almost visionary. But the urgency of water need would not be denied and, finally, when improvements in methods of construction and in construction equipment removed many of the impracticabilities, the project became possible. Actual work was begun in 1932. During the past few years the work has been vigorously advanced, and now only a few more months will elapse before the job will be finished and Colorado River water actually will be lifted some 1,600 ft. to cross the mountain ranges and to provide head for gravity flow through a major part of the long aqueduct.

That the water need is urgent becomes apparent from the fact that the dependable supply in the coastal plain, which will be about 1,000,000 acre-ft. annually when the present extension of the Owens Valley system is completed, not only must meet the domestic requirements of a population that now has reached 3,000,000, but also must provide irrigation water for 1,400,000 acres of arable land. At the rate of consumption usual in the Los Angeles region this supply is only about half the amount estimated as ultimately required. Even now there is constant and heavy overdraft on underground storage. The Colorado River supply will make unnecessary further drawdown of underground reservoirs, will meet the ultimate requirements of the region by just about doubling the quantity now available and will constitute insurance against periods of drought.

The aqueduct project had its inception in the vision and foresight of the late William Mulholland. More than a decade ago he foresaw an ultimate need far exceeding any water supply that could be developed in the coastal basin. With indomitable courage he persisted in the investigation and promotion of a plan for water importation that seemed almost impossible. Finally, as the result of his efforts, thirteen cities united to support the Colorado River aqueduct project, formed The Metropolitan Water District of Southern California, and put F. E. Weymouth in charge as general manager and chief engineer. Then followed the period of active construction described in this issue. However, no mere figures on distances and costs (some 400 miles and more than $200,000,000) can convey an adequate idea of the extremely adverse conditions under which desert construction was carried on, or of the repeated discouragements met in the exceedingly wet 13-mile San Jacinto Tunnel.

The Colorado River Aqueduct crosses mountain ranges and deserts to reach the Los Angeles region.

Throughout the undertaking there never has been the slightest ground for charges of waste, misappropriation of funds or political interference. Particular credit for this refreshing situation reflects upon Mr. Weymouth and on the board of directors. If either had been less effective, there would have been great risk of internal difficulties with resultant inefficiency and waste on the job.

Because the project has been one of the largest, most diversified and most difficult engineering undertakings in history, it has required a superior engineering organization. Nothing less than an able, loyal staff, imbued with high ideals and working together as a unit for a common cause, could have completed such a formidable job with the speed and efficiency attained. Full credit for selecting, organizing, and managing this engineering staff goes to Mr. Weymouth. He displayed knowledge

of human nature in high degree in choosing and directing his men. How well they have functioned is attested by the fact that now there is no question but that the great aqueduct will be made ready for operation, despite all difficulties, within the original time and cost estimates.

Progress in engineering

The saying that "the way to learn to do a thing is to do it" is particularly true on heavy construction because the needs of the job and the methods and equipment best suited to it often are not revealed until after the work is under way. Also, the incentive to attack difficult problems and the money for costly development of equipment is lacking until urgent need arises. On the Colorado River Aqueduct, incentive and need were present; on parts of the work the difference between success and failure hinged upon the ability to improve on old methods and to evolve new equipment.

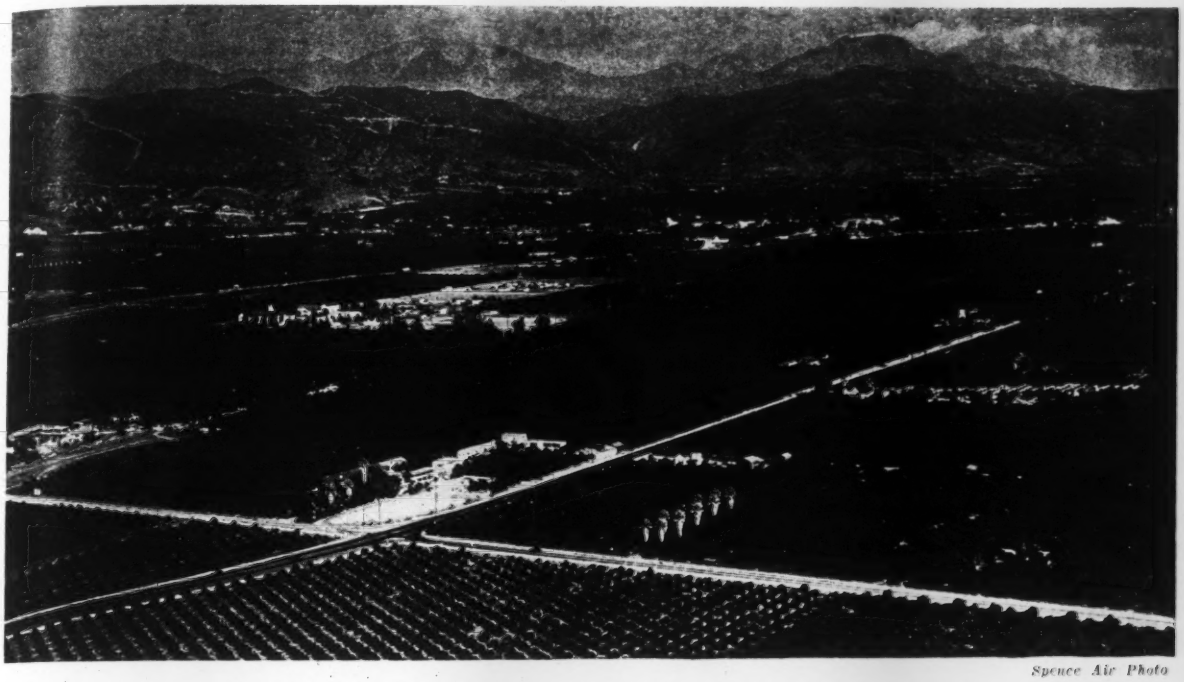
Human problems were perhaps on a parity with difficulties interposed by nature. Modern heavy construction has been mechanized to such an extent that a high percentage of workers must be trained for their specialties; organization of an efficient staff for carrying out a construction project in an isolated desert region called for leadership of a high order in the teaching and training of men and in cultivating an *esprit de corps*. With almost a hundred miles of tunnel to be driven on the Colorado River aqueduct, 90 per cent of the available workmen had never before been underground. Quite by accident (because the project started long before the era of "make-work" undertakings) the job reached the peak of construction activity in the years when relieving unemployment was a major problem. Thus it almost providentially met a national need by creating, in a very critical period, a demand for labor, materials, and equipment.

Special equipment designed

A notable feature of this work, partly because of its great size, was the incentive for advance and improvement of methods and equipment. Huge canal grading and lining machines evolved expressly for the aqueduct are now making savings in construction costs on other jobs; jumbos large enough to carry automatic feed drills for working a full-face tunnel heading helped to demonstrate the feasibility of something better than the old heading-and-bench methods; curved steel I-beams to replace segmental timber sets for tunnel support became popular and, with timber lagging, proved cheaper and quicker, under certain conditions, than the old methods; high pressure grouting practices developed in San Jacinto Tunnel established a precedent for deep, wet tunnel operations; the removal of dust from aggregate by air currents, where water for washing was not available, resulted in a new line of equipment; and welding of steel pipe plates as much as 1 in. thick, in the trench was proved to be feasible under the advanced methods applied on this job. By reason of the high premium on pump efficiencies, an extensive research program was carried out, with the result that efficiencies considerably higher than ever before attained in large pumps have been developed by design improvements. The need for this becomes apparent when it is realized that for full aqueduct flow power costs can be reduced $50,000 by each increase of one per cent in pump efficiency.

These are just a few of the contributions to engineering progress which are byproducts of an unprecedented undertaking. They constitute a legacy from this job to the profession—a heritage in the form of additions to the sum total of engineering knowledge that will make for greater economy of time and cost on construction work done in the years to come. —THE EDITORS

Construction of access roads was one of the first problems of the district staff.



Spence Air Photo

FIG. 1. INTENSIVE DEVELOPMENT SUCH AS THIS WILL BE PROTECTED BY IMPORTATION OF COLORADO RIVER WATER

Urgent Need For Colorado River Water

F. E. WEYMOUTH

General Manager and Chief Engineer, Metropolitan Water District of Southern California

Southern California history is a long record of struggles with drought culminating in a bold plan to bring water all the way from the Colorado River

SOUTHERN CALIFORNIA is on the eve of another victory in its long conquest of the desert. The construction of the Colorado River Aqueduct will soon pass into history and this great water project will begin to function as a vital factor in the development of the area that it is to serve. This transition will be of great significance. It will mark the culmination of a long hard fight by an ambitious and courageous community against the adverse forces of drought and desert.

The aqueduct is being constructed by the cities of Anaheim, Beverly Hills, Burbank, Compton, Fullerton, Glendale, Long Beach, Los Angeles, Pasadena, San Marino, Santa Ana, Santa Monica, and Torrance, through the agency of the Metropolitan Water District of Southern California. These cities are situated in an area known as the South Coastal Basin of California. That this basin is inherently a desert is not immediately evident to the recently-arrived resident or tourist, with only the luxuriant sub-tropical vegetation of the cultivated areas as a basis for judgment. The sharp contrast with the desert that must be crossed by incoming travelers increases the impression of abundant moisture. It takes much more than a casual inspection to realize that every green leaf and flower is continuously dependent on heavy, frequent irrigation.

The basin is closely encircled on the land side by a ring of hills which separate it from surrounding deserts of extreme sterility. There are no long rivers, bringing in water from distant points, and there are no nearby flows that are not already overexploited. The total area of the drainage basin involved is 3,900 sq. mi., about 2,200 sq.mi. of which are habitable. The remaining 1,700 sq.mi. of steep, rocky, mountain area is the only natural source of an outside water supply.

The average annual rainfall in the habitable portion of the basin ranges from 15 in. at Los Angeles to about 10 in. at the beaches. There is a slight increase toward the foothills and an average of as much as 30 in. over a small area in the mountains.

Such averages, however, are misleading. One very wet year such as 1938, when most of the runoff is in floods which waste into the ocean, outweighs several dry years in computing the average. As nearly as may be determined from old "Mission"

crop records, diaries, and other early reports supplementing the 60-yr. rainfall record of the U. S. Weather Bureau, 157 yr. of Los Angeles history have included 94 yr. with less than average rainfall and more than 100 yr. with less than average stream runoff. The median precipitation during the period has not exceeded 13.5 in.; that is, at least half of the years have yielded less than this amount.

Even this figure is not dependable because the dry years tend to come in groups and the damage caused by a drought rapidly mounts with its duration. Notable dry cycles occurred about 1791, 1809, 1828, 1845, 1858, 1863, 1877, and 1897 to 1904. The need for water during these dry periods was small compared to present-day needs, yet the suffering was acute. At the end of the last severe drought (1904), Los Angeles had about one-eighth its present population. A repetition of this drought could not be endured by the present population without aid from outside sources.

The extraordinary floods of March, 1938, unprecedented within a generation, and notable for rainfall intensities as high as 15 in. in 24 hr., serve to emphasize the usual deficiency of precipitation. In half of the states of this country, which contain about three-fourths the population, the most severe drought years ever recorded show more rain than fell during the last 12 mo. in Los Angeles and vicinity.

At this point, the reader may justly ask how the present development was ever built on such a meager water supply. The logical answer—that it wasn't—calls for explanations dating back to the earliest recorded history of the region.

Underground sources

The basin began its geological history as an area of hills and valleys, generally far beneath present ground levels. At the beginning of the present civilization, these valleys had become filled with debris and water, contributed by the surrounding mountains throughout countless thousands of years. Portions of this "backfill" were covered with a coating of impervious clay and finished off with a surfacing of fertile top soil. There was thus created—and hidden from casual view—a vast storehouse of fossil waters.

It was inevitable that there should be some overflow from the underground reservoirs, in the form of springs and small streams, sufficient in volume to relieve the already-filled basins of annual accretions from the limited rainfall. The result was a few perennial streams, flowing bountifully during the wettest years and maintaining at least a trickle throughout the most severe drought. On the banks of these streams, the early Spanish settlers built their missions and pueblos.

As these few spring-fed streams were the sole source of water supply during the long, dry summers, irrigation was limited. At Los Angeles, an irrigated area of 1,500 acres at the time of the American occupancy had grown to only 8,400 acres a generation later, and in 1879 even this small oasis suffered seriously from lack of water, much accentuated by increasing upstream diversions. These encroachments on the pueblo's ancient water right, on which the settlement's very existence depended, became the subject of long, drawnout litigation which finally restored the water to the town. Since that date, Southern California courts have seldom been free of involved and costly water litigation.

Losses in early days

Even the cattle industry, the main support of the region under Mexican rule, suffered enormous losses due to drought, particularly in 1856–1858 when 100,000 head died, and even more in 1862–1864. The ranchos never fully recovered from these losses. Sheep largely replaced the vanished cattle, but were soon equally hard hit by drought, 22,000 being recorded as lost in 1874–1877 on the Centinella Rancho alone.

As a result of these heavy and repeated losses, the great landed estates began breaking up. In the absence of present-day power resources, there was no thought of going underground for water to maintain pastures during years of drought.

Eventually a well was drilled through the impervious clay cap, into the gravels below, and a bountiful artesian flow came forth. The famine was over. Wells went down by the score, the railroads came, and the boom was on. By 1890, the artesian area had spread to 315 sq.mi. and every farmer and fruit grower had his own well. Extraction was easy, profitable, and uncontrolled. Naturally it was overdone. The peak of the artesian production came somewhere around the beginning of the present century when the U. S. Geological Survey found 2,500 wells yielding not less than 300 sec.-ft. In the meantime, pumping facilities had been improved and there were thousands of pumped wells outside the artesian area.

The rate of extraction became too much for Mother Nature. Pressures dropped, and one by one the artesian wells in the entire coastal plain ceased to flow. The 1930 census reported a total of only 22 flowing wells in the entire coastal plain. But the wealth built upon the foundation of abundant waters could not be abandoned. Pumps were installed, extractions continued, and frequently were accelerated. Water levels fell. Wells were deepened and more were drilled. Springs dried up so completely that their former existence is often entirely unknown to present residents. The beds of formerly perennial streams degenerated to dusty floodways. No expert examination was required to show that the water used greatly exceeded annual replenishment. Continued development demanded new water resources.

As water levels fell, the increased cost of wells and of power for pumping, as well as the accompanying scarcity of water, automatically encouraged the elimination of waste.

Attention was also turned to conservation of flood waters wasting into the sea. Precipitation falls almost entirely in a short wet season in winter. The few surface reservoir sites that were available are in use.

Use is also made of natural underground storage facilities. Farm lands are cultivated in such manner as to encourage the maximum absorption of rainfall. The surplus winter flow of streams is spread over untilled gravelly areas, to accelerate absorption into the underground basins. Stream beds are plowed and harrowed, to remove sod, break up silt cakes, and otherwise encourage percolation.

Owens Valley Aqueduct

Even with careful use and complete conservation, a 15-in. average annual rainfall is not enough. Early realization that water must be

brought in from outside the basin led to the construction of the Owens Valley Aqueduct, begun in 1907 and finished in 1913. This aqueduct, with a capacity of 450 sec.-ft., reaches 250 mi. northward to intercept the snow-fed streams along the eastern slope of the high Sierras. Even these sources partially failed in the late nineteen twenties, and the aqueduct was kept flowing only by pumping from wells hurriedly sunk into the gravels in the headwater area. The aqueduct is being extended 100 mi. further to the north, to collect additional waters from the Mono Basin.

The importance of the Owens Valley Aqueduct in the development of Southern California cannot be overestimated. When completed, it was expected to end water troubles in Los Angeles for an indefinite period, if not forever, but this was not to be. Development followed so rapidly that Los Angeles soon began again to look about for a new and still larger supply.

Remaining resources originating in the Sierras were found already overappropriated; the surrounding desert was too dry to afford relief. There was one, and only one, possible source—the flashy, turbulent, silt-laden Colorado River 300 mi. away, across an almost trackless desert.

In 1923, just ten years after the completion of the Owens Valley Aqueduct, disregarding obvious and apparently insurmountable difficulties, the late William Mulholland, then chief engineer of the Los Angeles Bureau of Water Works and Supply, began the active study of an aqueduct to bring in Colorado River water.

A Colorado River source

Prior to this time, the general problem of controlling and developing the Colorado had been intensively studied by the U. S. Bureau of Reclamation. The river drains an area of 247,000 sq.mi., ranging from the snow-capped peaks of Colorado and Wyoming to the arid deserts of Arizona and California. Although large quantities of water were wasting into the sea, the flow of the river was erratic. Enormous floods, which threatened the lower river areas with destruction, followed flows too low to meet the minimum needs of areas already under cultivation. Volumes had been written on proposed plans of development. The late A. P. Davis, as chief engineer and later as director of the U. S. Bureau of Reclamation, was vitally interested in the control and utilization of this great national resource. A comprehensive report, prepared under the direction of the writer as chief engineer of the U. S. Bureau of Reclamation, issued Feb. 28, 1924, discussed in detail the merits of possible development plans, and recommended storage at the present Boulder Dam site as a logical first step.

The problem was gigantic. The entire drainage basin is arid and the river flow is its life-blood. There were many conflicting interests and jealousies to be overcome. Seven independent and sovereign states were involved. The federal government, the only agency in a position to attack the problem, was hampered by conflicting political influences. Progress at times seemed at a standstill.

Early studies contemplated development for flood control and irrigation only. Prospective returns from water sales were inadequate to repay the cost of the project, but there were important power possibilities. Los Angeles and the surrounding territory offered an attractive market for power. The injection of the domestic water supply problem, and the proposed Colorado River Aqueduct, added impetus. The delivery of Colorado River water into the coastal area required large-scale pumping and this increased the demand for power.

Events move forward through a maze of legal, diplomatic, and political complications, to culmination

Fig. 2. **The rugged nature of much of the desert region is indicated by the picture of Eagle mountain siphon. For scale, note the man standing on the crest of the siphon. The excavation at the left is for a second siphon.**

in the passage of the Boulder Canyon Act by the 70th Congress in December, 1928. Before this act became effective, it was necessary that at least six of the seven Colorado River basin states should ratify the compact upon which it was founded, and that the Secretary of the Interior should secure firm contracts for the sale of power sufficient, in his judgment, to return construction costs with interest at 4 per cent, within a period of 50 yr. These conditions were complied with and Boulder Dam was approved for construction on July 7, 1930.

In the meantime, interest in Colorado River water had broadened to include all of the principal cities of Southern California. The need for water was recognized as basin-wide, and the advantages of concerted action were evident. Legislative authority for the required organization of noncontiguous areas was secured in 1927. The Metropolitan Water District of Southern California was incorporated Dec. 6, 1928; organization was completed Feb. 9, 1929. Funds from a small tax levy, sufficient for preliminary work, became available in 1930. Prior to that time, a considerable amount of investigational work had been done by the Los Angeles Water Bureau. On May 1, 1930, all records accumulated by the city and all activities concerning the Colorado River Aqueduct were taken over by the district.

Aqueduct capacity

A difficult problem in planning the aqueduct was the determination of its ultimate capacity. That draft on local sources exceeded replenishment was evident, but determination of the actual amount of overdraft involved many complexities. An aqueduct from the Colorado River to be economically feasible must be adequate for future needs of a rapidly developing territory.

A conservative estimate of the annual overdraft on underground water storages in the metropolitan portions of Los Angeles, San Bernardino, Riverside, and Orange counties, as of 1929, was 200,000 acre-ft. Careful estimates placed the importation required to offset this overdraft and provide for future growth at not less than 1,000,000 acre-ft. per year. By extending the benefits of the aqueduct to immediately adjacent areas, the estimated need can be doubled, and by going outside the coastal basin into the surrounding desert area, a still larger market for water can be created.

However, the marginal areas were not ready to participate in the proposed water project, and the cities were not prepared to undertake provisions for the uncertain future needs of these areas. Moreover, the coastal plain is outside the Colorado River basin and any appreciable diversion for purely agricultural uses would have met serious opposition.

Diversion set at 1,500 sec.-ft.

The net result of the study was to set the diversion at 1,500 sec.-ft. continuous flow, which is about 1,100,000 acre-ft. per year. This quantity will be absorbed within the environs of the present four-county metropolitan area, and will come reasonably near fulfilling its ultimate needs.

Coincidentally with the civic, economic, and hydrographic studies, an intensive program of preliminary surveys was inaugurated. The strength of the desert was carefully measured to make sure that the water so badly needed was economically attainable. Finally, after a widespread search, an acceptable aqueduct route was found. Estimates showed the cost to be great but not prohibitive. By the middle of 1931, the loose ends had been fairly well brought together. The district had made contracts with the government for the delivery of 1,100,000 acre-ft. of water per year from the reservoir to be created by Boulder Dam, and for a large block of Boulder power to be utilized for pumping this water over the mountains. A route had been selected and an estimate was ready for submission to the voters.

Financing the project

At an election on Sept. 29, 1931, a $220,000,000 bond issue was approved by a five-to-one majority. Then followed a period, prematurely considered the depths of the depression, when sale of the bonds seemed impossible. Finally, an amendment to the act governing the Reconstruction Finance Corporation, then recently formed, solved the problem. On Sept. 13, 1932, the aqueduct received the first of the R.F.C. self-liquidating loans for public works in an amount of $40,000,000.

Too much credit cannot be given the R.F.C. for the admirable manner in which it aided this undertaking. An important feature was making bond funds available in relatively small amounts as required, thus reducing to a minimum interest during construction, which has all been paid from taxes. The original interest rate of 5 per cent was rebated to 4 per cent during construction. The original bonds recently were refunded at an average rate of 4⅛ per cent, instead of the 4¾ per cent on which the original project estimates were based. This reduction means a total interest saving of about $40,000,000.

Several attempts were made to finance portions of the project with PWA funds, on a combination loan and grant basis. A loan of $1,500,000 and a grant of $600,000 obtained for river control at Parker Dam were the only funds secured from PWA.

Organization and personnel

The great size and the unprecedented difficulties of the project in a way helped to carry it through to a successful conclusion because they drew to the work, through the staff and consulting boards, the best engineering talent of the nation. Construction operations were of such magnitude and divisibility as to attract both the largest and smallest contractors. Competition has been keen and clean-cut throughout.

More than 45,000 men have had productive jobs on this project; wages paid directly to local residents have amounted to $55,000,000. This on a project free from earmarks of the "make work" job. The fact that employment has been restricted almost exclusively to residents was no detriment in this case. The industry and cheerful loyalty of the men who have contended with floods under high pressure in San Jacinto tunnel, fought caving rock in other tunnels, and faced desert temperatures approaching the limit of human endurance, deserve the highest praise.

One of the most important elements in the success of the undertaking has been the steadfast support of the staff by the governing board of directors. This board consists of 19 men of outstanding ability, representing the 13 cities of the district.

They have, with remarkable unanimity, supported the management in keeping favoritism and political influence strictly and entirely out of the district's business.

Looking backward, it now appears that the project could not have been undertaken at a more fortunate time. It has had the advantage of favorable labor and material markets. Much good has been accomplished by supplying worthwhile jobs in a time of need.

It is now assured that the project as originally planned will be completed well within its estimated cost. Its replacement cost, if started now under prevailing labor and material cost conditions, is estimated at not less than $300,000,000.

To have been closely associated with this project during its planning and construction has been an inspiring, even though wearing, experience.

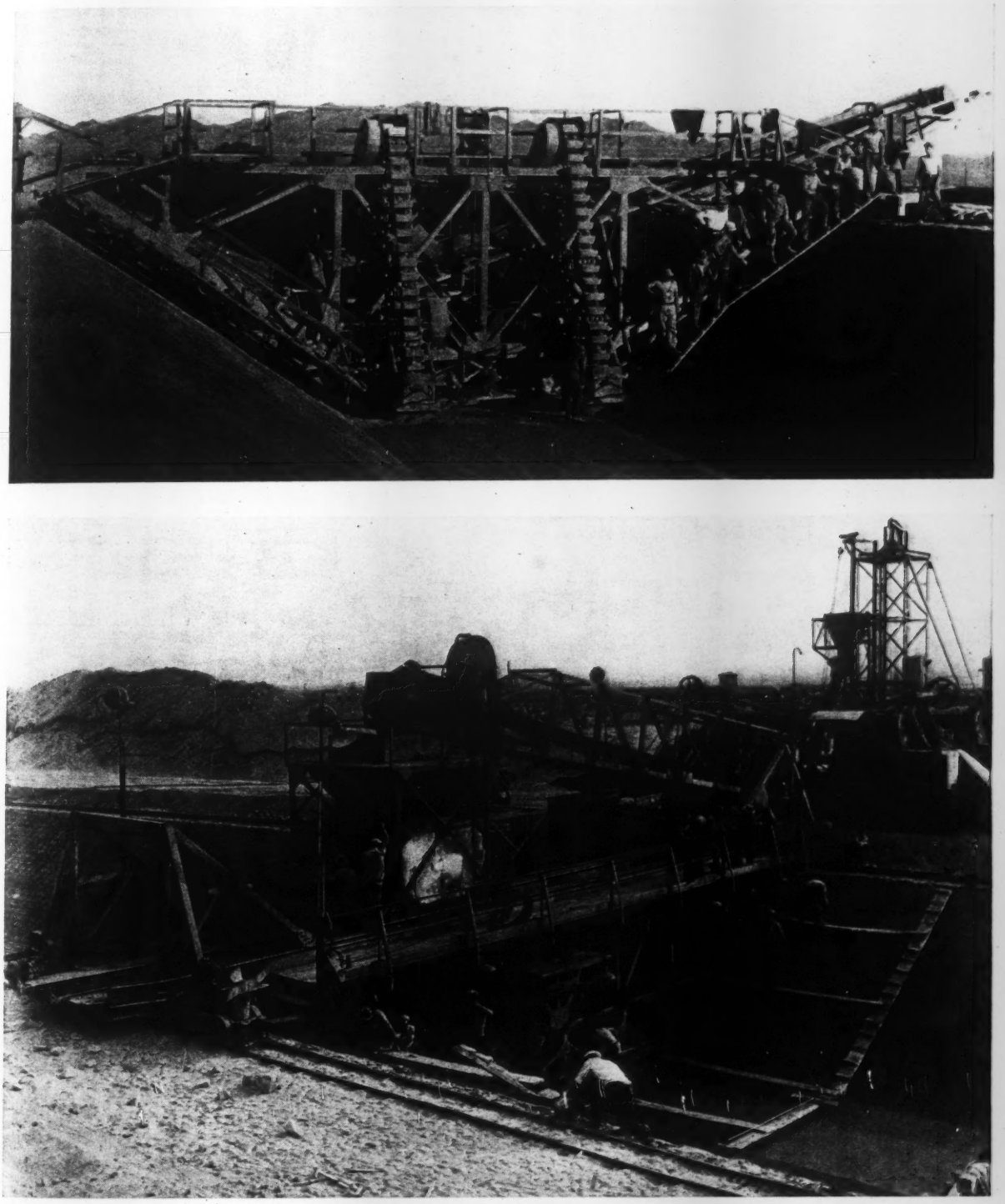
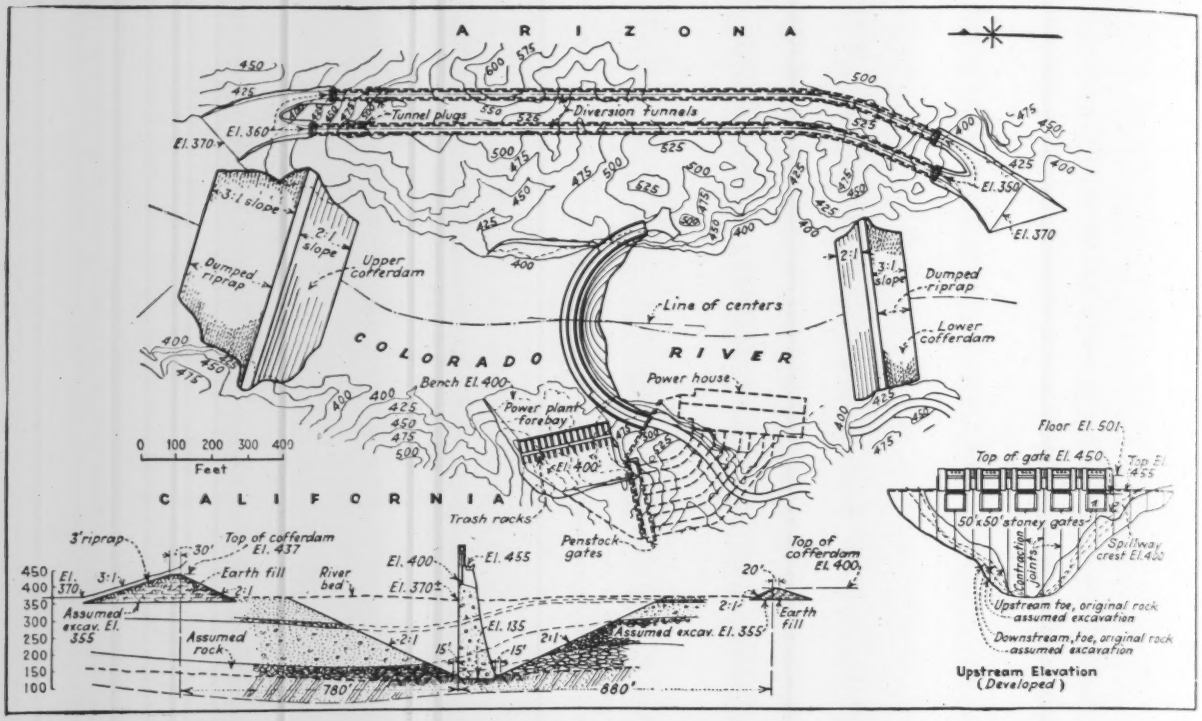
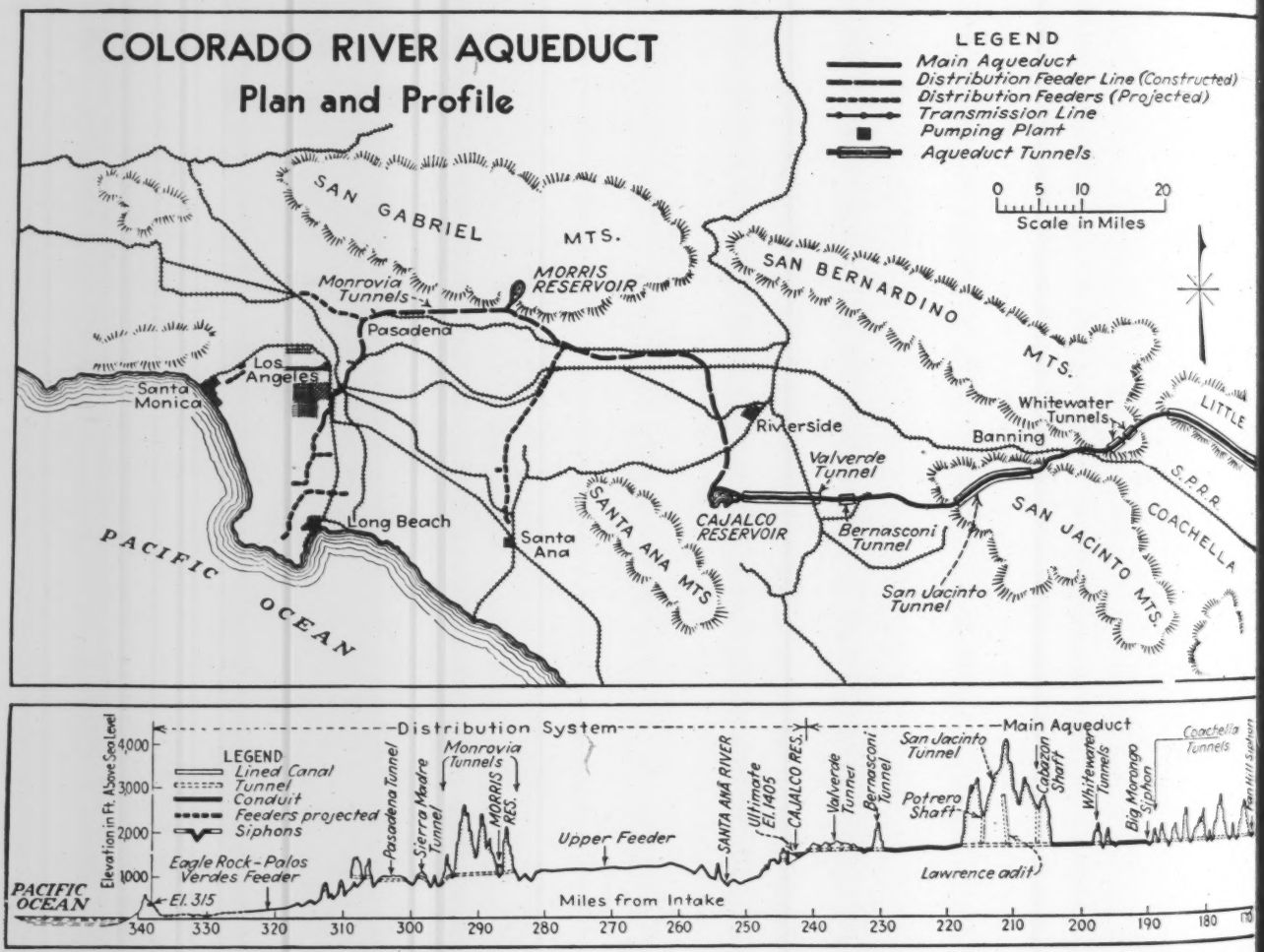


Fig. 3. Construction equipment especially developed for the aqueduct included canal graders (top) and canal lining machines.

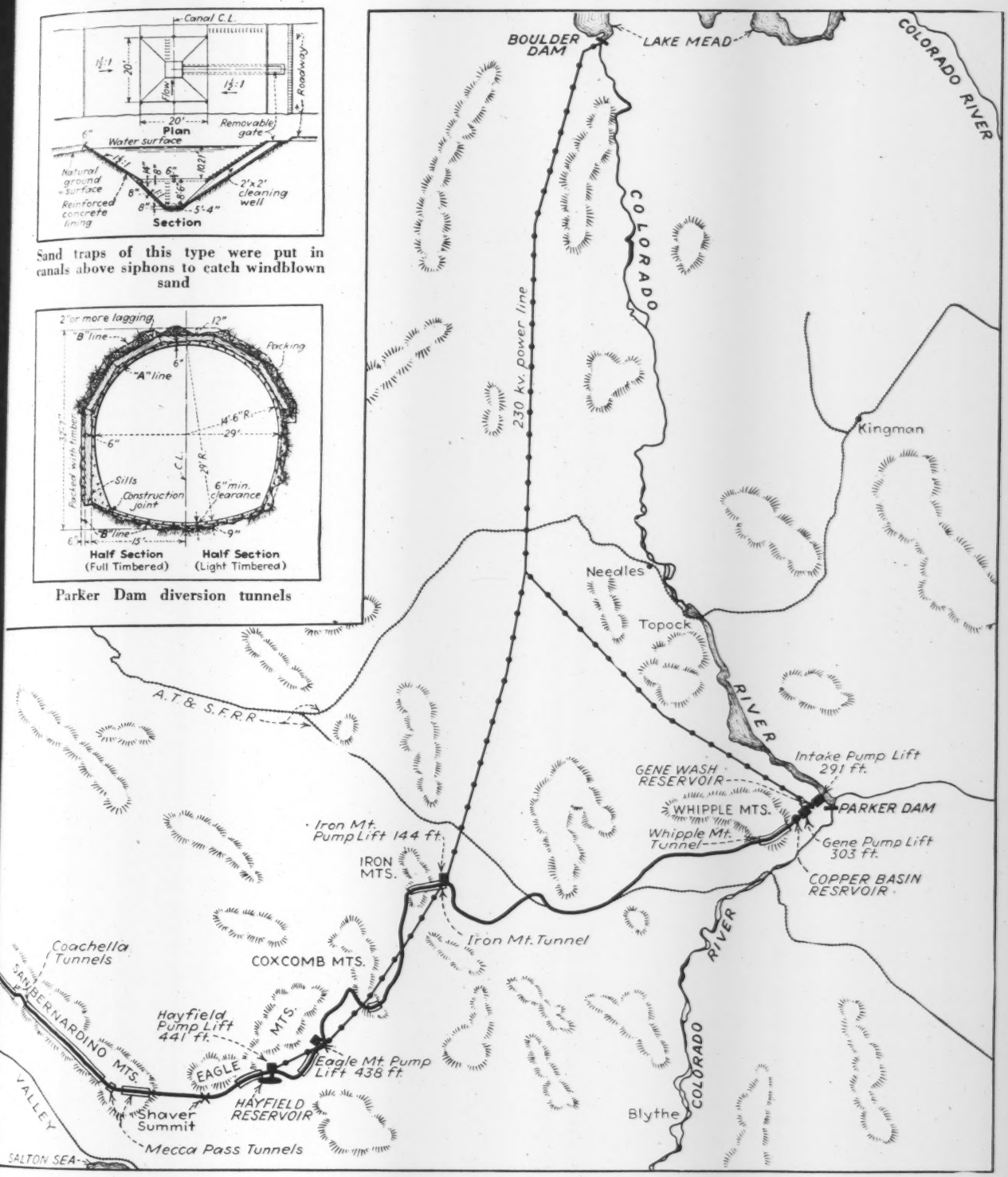


PARKER DAM PONDS COLORADO RIVER WATER FOR THE AQUEDUCT AND FOR POWER.



Sand traps of this type were put in canals above siphons to catch windblown sand

Parker Dam diversion tunnels



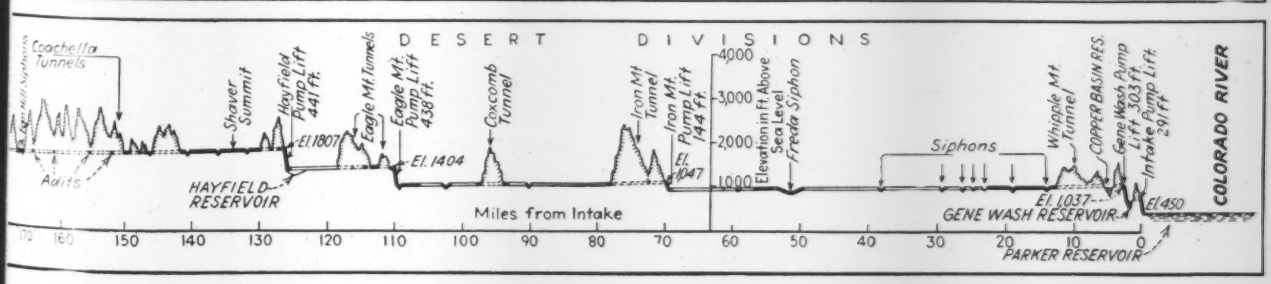


FIG. 1. ENGINEERS HAD TO WORK IN THE MOST FORBIDDING DESERT WASTES TO TAKE TOPOGRAPHY

Major Problems of Aqueduct Location

JULIAN HINDS

Assistant Chief Engineer, Metropolitan Water District of Southern California

Hundreds of miles of heretofore unmapped desert required thorough examination prior to deciding where to divert, whether to use gravity or pumps

PLANNING for construction of the Colorado River aqueduct consisted of three distinct stages: (1) that which led up to a decision that increased water supply for Southern California must be imported from the Colorado River; (2) selection of the best aqueduct route, and (3) actual design of the numerous structures and preparation of detailed plans. This article is devoted to the second of these three phases. It begins with the decision to go to the Colorado River for the new supply and takes the reader back and forth across the desert in studies preliminary to selecting the point of river diversion, locating the aqueduct itself, deciding whether to use a gravity system or a pump supply and where to put storage reservoirs, pumping stations and other essential features. Thus in this article the reader is given an outline of what was done to make ready for the horde of engineers in field and office who finished up final location surveys and prepared detailed designs for the builders soon to follow.

When the time came to select the aqueduct location, no data were available on which to base even the most preliminary plans. A considerable length of the river lies approximately on the arc of a circle centering in Los Angeles. Thus a number of diversion points offered about the same length of line. As if to complicate the problem, other lines of greater lengths had compensating advantages. Geology, topography, accessibility and other factors had to be considered in comparing hundreds of possibilities among which there was no general route so outstanding that it could at once be selected as evidently best. A general reconnaissance failed to yield definite indication favoring any particular route.

For more detailed study the first requisite was contour maps, and none had been made on much of the area to be studied. This resulted in topographic surveys of unprecedented scope; contour maps were made for an area of 25,000 sq. mi., much of it in the most forbidding of desert wastes. These maps were of vital importance in the search for the best location.

As the work progressed, new possibilities developed. Convergence toward a definite plan was slow. Surveys and estimates were made on lines that covered the entire desert area between the river and the coast. These lines were not in a symmetrical or uniform pattern, rather they formed an irregular network, knotted together by controlling geographical features.

Like wagon trails of the pioneers, aqueduct locations all headed for mountain passes to avoid the long, treacherous tunnels required by more

direct alignments. Where the wagon trails went over the tops of the passes, the aqueduct could not follow because of limiting grades or excessive pumping costs. The controlling divides, rather, had to be passed in tunnels, and mountain passes often are not good tunnelling ground. They usually represent weak spots in the mountain barrier where the rock is broken, easily eroded, and subject to caving. Some of the passages into the coastal area are traversed by active earthquake faults and many are water logged. A careful geological study of controlling passes had an important influence on the final selection of the aqueduct route.

Gravity supply impracticable

A number of the first lines investigated involved no pumping. Popular opinion among water men and laymen favors a gravity supply for a metropolitan area, and it was natural that many of the schemes proposed gravity delivery. One ambitious plan contemplated a high dam on the Colorado River and high-level diversion at Glen Canyon, far upstream from the Grand Canyon, with a waterway some 850 mi. long, serving, on its way to Los Angeles, large areas in Utah, Nevada and California. Another scheme contemplated a diversion dam possibly 900 ft. high in Bridge Canyon, near Kingman, Ariz., with a gravity line to the coastal area. Such plans involved, in addition to other difficulties, tunnels of great length—sometimes under mountain ranges and sometimes deep down under water-filled, alluvial plains.

An interesting proposal was a single tunnel from a low point in the valley just east of Los Angeles, straight into the reservoir at Boulder Dam. This tunnel would be deeply buried in alluvial fills and would pass under, rather than through, mountain ranges known to be badly fractured and faulted. Even this location would not have entirely eliminated pumping. Its terminal elevation was about 500 ft. above sea level, well below much of the area in need of the new water supply.

Each of the gravity schemes was carefully considered. In the end it was necessary that all be dismissed as impossible or at best involving a cost out of all proportion to benefits. Thus the project acquired a pumping problem.

Economics of a pumping project

In the study of pumping projects the first step was the establishment of a basis for determining the economic relationship between cost of pumping, length of aqueduct, percentage

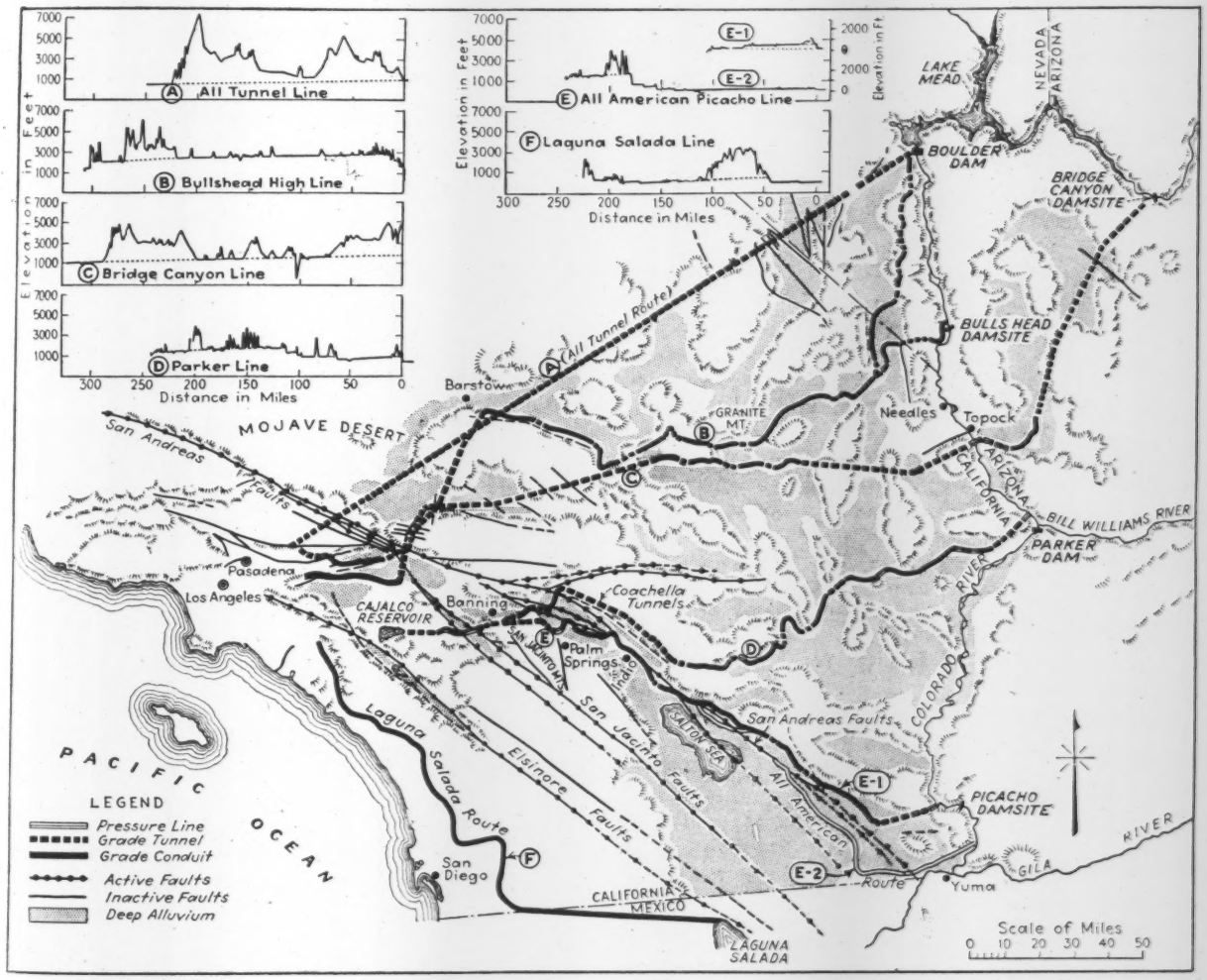


Fig. 2. Numerous routes were carefully studied to determine the most practical location for an aqueduct.

of tunnel in the line, and size and type of conduits.*

It was necessary to provide a pump lift sufficient to permit economic crossing of the mountains dividing the coastal area from the desert, and to furnish the fall required to maintain flow in the aqueduct.

Balancing cost factors

On none of the lines studied was the grade elevation of the tunnel through the controlling divide definitely fixed by physical factors. Tunnels could be raised or lowered appreciably without running into insurmountable difficulties. However, the length of tunnel, and usually the length and depth of approach cuts varied with the elevation. Lowering the tunnel increased its cost, but reduced the pump lift and, consequently, the cost of pumping. It was necessary that these factors be carefully balanced. Beyond a certain point, each foot of lowering added disproportionately to the length of tunnel and to the cost of approach cuts. The economic elevation was indicated by the point at which the increase in tunnel costs began to exceed the reduction in pumping costs.

The amount of fall required for the maintenance of flow likewise was subject to variation. If a water conduit is given a very steep slope, the water will flow rapidly, enabling a small channel to deliver a large flow, thus keeping costs down. For each type of conduit, there was an "economic slope" which gave the smallest combination of construction cost plus the cost of building and operating the pumping plants. Because of the many variable factors, the economic size also varied. Theoretically, a different size should have been used for each type of conduit for every location on all of the many alternatives. Practically, much standardization was possible.

Although pumping costs, as well as construction costs, varied with location, these variables were more or less constant for plants on any of the favorable lines, assuming that pumping is done away from Boulder Dam. Hence it was possible to develop an average figure for use in comparing pumping costs on different locations. This figure, set at $65,000 per ft. of *additional* lift, included the influence of added lift on the cost of building transmission lines, pumping plants, delivery lines, and all other required facilities, plus the capitalized value of future operating costs.

Application of these economic principles to the analysis of the many alternative lines was not a simple mathematical matter. Mature judgment on the part of the locating engineer was a constant necessity. The line must start at a safe diversion point where the river could be controlled under all conditions of flow, and where facilities for clarifying the muddy river water could be provided at reasonable cost. The line must end at a point convenient for distribution, and where terminal storage facilities were available. Also it must be safe from undue hazard of flood, wind, and earthquake.

Boulder Dam offered the most obvious opportunity for diversion. Pumping at that point would cost less than elsewhere, and the low water level of 895 ft. in Boulder reservoir is considerably higher than the river level at other available diversion points. However, the mountain passes along a direct route from Boulder are higher than for other possible lines, requiring a high summit elevation, and the route is longer, requiring more fall for the maintenance of flow. The pump lift on a line direct from Boulder was actually greater than required on shorter and cheaper lines. Two other factors were that topographic conditions would permit only a portion of the pumping to be done at the intake, and the district's power contract required that the government be reimbursed for power lost due to diversion above Boulder Dam.

Any permanent diversion other than from Lake Mead would require some form of diversion structure in the river. Below Black Canyon the river bed has been deeply eroded and refilled with silt and gravel. At many places the alluvial bottom lands are of great width and the channel of the river shifting. Such places do not offer attractive diversion possibilities. Even in the few available narrow passages, the depth to bedrock is great. A low "floating" weir was evidently the most economical type of diversion structure. But with such a diversion, storage space for the removal of silt would be negligible and auxiliary clarifying equipment would be needed. Complete clarification is important to avoid damage to the high-head, high-efficiency pumps. The cost of clarification, estimated at several million dollars, imposed an important handicap on a low diversion structure.

Opportunities for a high dam with appreciable reservoir space above it were limited. Such possibilities were investigated at Bullshead, Topock, Parker and Picacho, respectively, 67, 113, 155, and 285 mi. downstream from Boulder Dam.

Borings revealed unsatisfactory foundation conditions at Picacho; Topock was ruled out by flowage conditions for the reservoir. Satisfactory foundations were found at Bullshead and Parker.

Parker route selected

In the final selection of a route, the estimated cost of diversion, including clarification works, was added to other estimated costs and considered with all other essential factors. A line diverting from a reservoir above a dam to be built at the Parker site was finally chosen as most desirable. Parker Dam raises the water 72 ft. thus reducing the pump lift at the same time that it provides 717,000 acre-ft. of storage which will control silt inflow for an indefinite period and makes possible the development of 80,000 hp. The resulting aqueduct follows a safe and convenient location, entering the coastal plain by a tunnel through an arm of Mt. San Jacinto in the San Gorgonio Pass, south of Beaumont.

Conditions at the ends of this tunnel determined the general elevation of the aqueduct. The normal water surface at the tunnel outlet is at El. 1,505. Any further lowering would have rapidly increased the cost of approaches, particularly at the outlet where groundwater conditions are bad. On the economic slopes adopted, a total fall of 562 ft. is required to maintain flow in the 217 mi. of aqueduct between the intake and the San Jacinto outlet; with water at El. 450 in Parker reservoir, the resulting pump lift is 1,617 ft.

The ideal plan would have been to do all the pumping at a single point, i.e., at the intake. However, the desert floor, where it leads away from the Colorado River, is too low to support an aqueduct 1,617 ft. above intake

* See "Economic Water Conduit Size," by Julian Hinds, *ENR* Jan. 28, 1937, p. 113 and "Economic Sizes of Pressure Conduits," by Julian Hinds, *ENR* Mar. 25, 1937, p. 443.

Fig. 3. After diversion at Parker was decided upon, a scale model emphasizing topography aided in the final aqueduct location.

level. The ground rises gradually to Shaver's Summit, about 130 aqueduct miles west of the intake. Location of pumping plants was controlled by topography; five plants were decided upon, distributed as shown in the profile, p. 645.

Principles of location

The principles followed in distributing the pumping plants and locating the aqueduct between them are indicated in Fig. 3, a picture of a model of the east end of the route. The river is represented by the white line, *A E B C D*. Parker Dam is located at *B* where the river is lost from view in the narrow canyon. The diversion is made at point *E* by a pump lift of 291 ft. delivering into the small Gene Wash reservoir; then comes a second lift of 303 ft. into Copper Basin reservoir. On Fig. 3 these two reservoirs are shown as white spots near the river. The location from *E* to *F* is in tunnel because the terrain is too rugged for any contour type conduit. The total distance from the intake to point *F* is 11.9 mi., made up of 0.6 mi. of delivery line, 0.5 mi. of pipes and siphons, 1.3 mi. of passage through reservoirs, and 9.5 mi. of tunnel. West of point *F*, surface conduit was possible for a long distance.

The combined height of 594 ft. for the first two pumping lifts was determined by conditions at the two saddles, *G* and *H*. The lift must be sufficient to clear saddle *G*, but not so high as to greatly increase the cost of the siphon across the low point at *H*. A third pump lift was required at Iron Mountain, point *I* in Fig. 3, to shorten the length of Iron Mountain tunnel and to improve location beyond. This lift was limited to 144 ft. by elevation of the saddle at *J*; the line then passes through the Coxcomb Mountains *(K)* and reaches the fourth pump plant at the foot of Eagle Mountain *(L)* where the lift is 438 ft., sufficient to deliver the flow around the corner of the mountains northwest of Desert Center (see map on page 645) and into Hayfield reservoir.

Beyond Hayfield, the terrain slopes up rather quickly to Shaver's Summit, the highest saddle east of San Gorgonio Pass. The fifth and last pumping plant, with a lift of 441 ft., has its intake in the Hayfield reservoir. The resulting maximum water surface at El. 1,807 ft. is somewhat more than required to clear Shaver's Summit. The excess was decided upon to provide head for passing the San Jacinto summit without further pumping.

Fig. 3 also shows why the diversion was placed at point *E* rather than at some nearer point, such as *C* or *D*. An excellent dam site existed at *B* with ample opportunity for a clarifying reservoir, and short delivery lines from the first two pumping plants. Incidentally, at *B*, the dam raises the water 72 ft. and affords opportunity for developing power from flow that continues down the river. A low weir would have been possible at point *C* but expensive clarification works and very long delivery lines from *C* to *F* would have been required.

A diversion at *D* would have appreciably shortened and cheapened the line but stable diversion works at that point were impossible and in any event, perpetual clarification would have been necessary. All factors considered, diversion at *E* (Parker Dam) was the most economical and most satisfactory.

Tunnels total 92 miles

Although tunnel costs much more per linear foot than surface conduit, 38 per cent of the main aqueduct length (92 mi. out of the total 242 mi.) is in tunnel. The necessity for this is revealed by a study of Fig. 3 and the map on p. 647. The terrain from *E* to *F*, Fig. 3, is far too rough to permit the economic use of a surface conduit; hence, tunnel was necessary. West of point *F*, surface line was used to point *I*, where the

alluvium talus slope of the Iron Mountains dropped down below the required canal grade. A sidehill line along the rock cliffs around the north end of the mountain was impracticable; hence, the mountain was tunneled. Similar situations required tunnels at Coxcomb Mountain, (point *K*, Fig. 3) and elsewhere along the route.

The Coachella tunnels, north of Indio and Palm Springs, constitute the longest and most continuous group of tunnels on the aqueduct. They are parallel to and near the face of the Little San Bernardino mountains where talus slopes drop away from a rough mountain side to the below-sea-level floor of the Coachella Valley. Any kind of contour route along these rugged slopes was impracticable, and the only alternative was a series of tunnels, set back into the mountains to clear most of the draws, but close enough to the surface to permit frequent access by adit.

One of these, the East Coachella tunnel, with an uninterrupted length of 18.3 mi., is the longest on the aqueduct. It was divided by four adits into five sections. San Jacinto, Bernasconi and Valverde tunnels were required to pierce high ground lying squarely across the adopted line.

Influence of geological conditions

After final location was settled, a careful geological study was made of the entire line, to gain as much information as possible concerning formations. If there had been likelihood of much heavy ground or of appreciable flows of water in the Coachella tunnels, the resultant hazard might have been great enough to make the Parker route impracticable. Consequently, the geology of this area was minutely studied. Good ground, slightly broken but dry, was predicted. It was expected that supports would be required in not over 10 per cent of the total length of these tunnels. (During construction it developed that the length actually supported amounted to 67 per cent, but in general relatively light supports were sufficient, and really heavy ground totaled less than 1 per cent. Very satisfactory speed records were made, and the work was completed well within the original estimate.)

The San Jacinto tunnel obviously would be wet, but rock conditions were exptected to be fair. Its location was changed many times in accord with information gained from geological studies and borings. Ground conditions were actually somewhat worse, and water conditions appreciably worse, than expected.

Active and inactive faults

Although portions of Southern California are notably seismic, the aqueduct system generally avoids danger of damage from earth movement. There is no evidence of faulting in recent geologic time in the desert area between the intake and a point in Morongo Canyon, north of Palm Springs. At this point, the line encounters a system of faults, including the San Andreas, lying along the north rim of the Coachella Valley. The San Andreas fault, which extends from Imperial Valley to San Francisco and cannot be avoided by the aqueduct line, is one of the world's most important active earthquake faults. Another important fault system crosses the aqueduct location just west of the outlet portal of the San Jacinto tunnel.

It was desirable that faults be crossed at right angles, to minimize damage in event of movement, and that some flexible type of conduit on or near the surface be used so that if repairs become necessary they will be as simple as may be. An articulated concrete pressure line was used for all fault crossings where there was thought to be any danger of movement. Although movements on all these faults have historically been horizontal, drops of 2.5 ft. are allowed at Mission Creek, San Andreas, and San Jacinto fault crossing to compensate for any possible adverse vertical displacement. Except in the three regions mentioned the main aqueduct is free from any evidence of recent faulting.

The San Jacinto tunnel, in the course of its 13-mi. length, traverses granitic formations containing numerous faults and fractures, but no evidence of geologically recent movement. In the distribution system, where some active faults are encountered, the precast concrete and welded steel pipe, which are extensively used, are more adapted to slight displacements than is monolithic construction. Moreover, cross connections, sectionalizing valves, and reservoirs increase the safety factor as to continuity of flow.

Neither the water supply at the intake nor the demand at the outlet are naturally constant, but for maximum efficiency the aqueduct must be kept running continually. Storage is required at the river and to equalize flood flows, and at the outlet to adjust the uniform aqueduct flow to variable seasonal demands of the area served. Headwater storage is amply provided in Lake Mead without taking into account the usable storage in Parker reservoir.

Storage facilities

At the end of the main aqueduct, an initial storage capacity of 100,000 acre-ft. is provided in Cajalco reservoir. This basin may be increased later to a capacity of 225,000 acre-ft. when required. Additional storage of 39,000 acre-ft. is being provided in the Morris reservoir, on the distribution main leading to Eagle Rock, and small operating basins are contemplated at other points.

Intermediate storage is provided in Hayfield reservoir, a natural basin, ordinarily dry, just east of Shaver's Summit, with a capacity of 86,500 acre-ft. This storage is available for pumping to maintain aqueduct flow in case of a break upstream from this point. Gene Wash and Copper Basin reservoirs, 6,300 and 20,700 acre-ft. respectively, serve as regulatory basins for the two pumping plants at the river. These two basins will be valuable aids in the removal of any turbidity coming from floods out of local tributaries to the Colorado River.

Selection of conduit types

In selecting conduit types, tunnels and pressure pipes, i.e., inverted siphons across drainage channels and depressions, were used only where unavoidable, because they are much more expensive than non-pressure, contour conduits. The cheapest type of surface conduit is an unlined, open canal. Excessive loss of water was highly undesirable and hence unlined waterways were inadvisable. The cheapest permissible type was a concrete-lined canal. This type was used only where cross-drainage can be controlled so that possibility of damage by storm waters is remote. To make open canals as dependable as

possible a very safe and permanent design was adopted, including reinforced lining from 6 to 8 in. thick. A comprehensive system of drainage ditches, dikes, and spillways was provided for protection. Provision also was made for the removal of any sand or silt brought in by wind or floods; aquatic growths will be removed if necessary. Open canal was used only to the east of Hayfield reservoir — all such construction (total length 62.8 mi.) is enclosed by wire fencing.

Where the terrain is rough, where cross-drainage or blow sand conditions bad, and for all surface lines west of Hayfield, an enclosed conduit is used, built in trench and backfilled.

Under favorable topographic conditions, open, lined canal costs less than half as much as covered conduit, and requires about one-third as much fall. The combined saving in construction cost, plus reduced capitalized pumping cost, through the use of 62.8 of open canal, amounted to more than $15,000,000.

Conduit capacities

The district's water right is limited to an ultimate average annual diversion of 1,500 sec.-ft. To allow for inevitable interruptions in flow, adequate capacity was set at 1,605 sec.-ft. This allows 7 per cent outage time for inspection, cleaning, and repairs.

Full aqueduct flow will not be needed immediately upon the completion of the aqueduct; perhaps not for 40 to 50 years. Because of this situation, consideration was given to the possibility of building the aqueduct in stages. Comparative estimates were prepared for one-third, half, and two-thirds capacity flows. For lined canals, covered conduits, and tunnels, estimated costs reduced relatively little as the capacity was reduced. Estimates for half-capacity construction ran from 80 to 85 per cent of full capacity. Such small savings did not justify divided construction. To confirm these estimates, alternate quotations were asked on full-capacity and half-capacity construction on a number of tunnels. The results are listed in the following table.

BIDS ON PART- AND FULL-CAPACITY AQUEDUCT

Tunnel	Low Bid		Cost half-capacity (percentage of full capacity)
	Full capacity (Dollars)	Half capacity (Dollars)	
Bernasconi	412,055	354,097	85.93
Valverde	3,286,603	2,861,180	87.06
Iron Mountain	3,843,504	3,190,137	83.00
Coxcomb	1,529,400	1,368,936	89.51
Cottonwood	1,857,062	1,521,879	81.95

Conditions for pressure pipes presented a different situation. Where the pipes were long or the heads high, practical considerations made it desirable to use double-barreled construction, even if the full capacity were required at once. Here, evidently, one barrel could be deferred. Hence, all important pressure lines are built to half capacity, with terminals set in ready for the duplicate barrel.

Pumping equipment likewise was planned in units. Each plant will contain a number of separate pumps which will be installed one at a time as the demand for water increases. Storage and distribution facilities are similarly subject to progressive development.

Advantages of location

The advantages of the aqueduct location finally selected may be summed up as follows:

(1) Permanent diversion facilities and perpetual clarification afforded by Parker Dam.

(2) Security from serious or permanent damage from earthquake or storm.

(3) Adequate regulatory and protective storage reservoirs available at reasonable cost.

(4) No insurmountable construction difficulties.

(5) A permanent water supply could be delivered over this route at a smaller cost, including capital and operating costs, than on any alternative route.

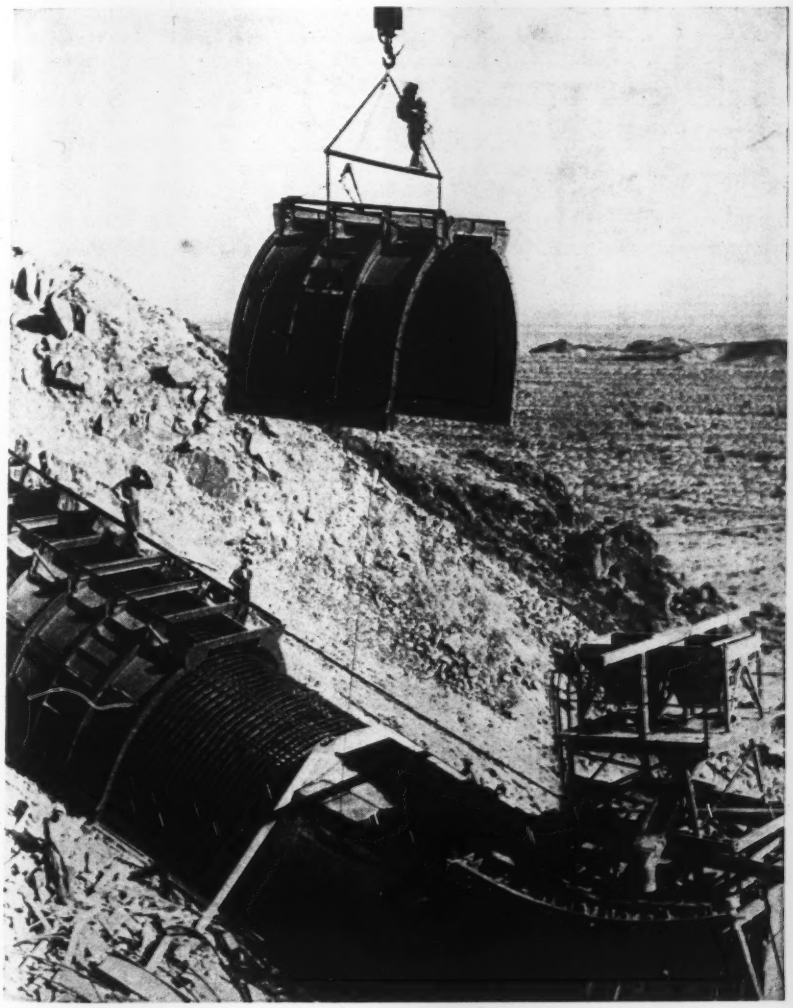
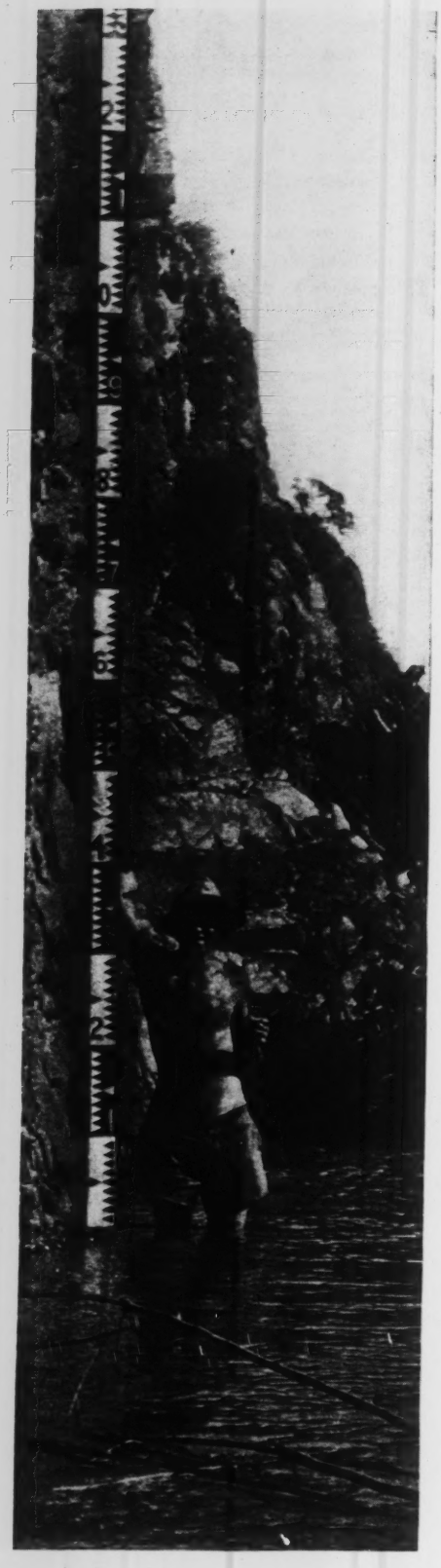


Fig. 4. Placing forms for Eagle Mountain siphon.

Men Responsible for Design and Construction of the Aqueduct



From 1923 to 1928 preliminary studies and surveys were under direction of the Los Angeles Bureau of Water Works and Supply whose engineering staff included:

William Mulholland.....Chief Engineer
H. A. Van Norman.....Asst. Chief Engineer
E. A. Bayley.....Chief of Field Surveys
Sidney L. Parratt.....Asst. Chief of Field Surveys

Since 1928, when the Metropolitan Water District of Southern California was formed, that organization has directed the work. Principal officials are as follows:

BOARD OF DIRECTORS

W. P. Whitsett.....Chairman
Franklin Thomas.....Vice-Chairman
S. H. Finley.....Secretary
Charles H. Toll.....Treasurer
D. W. Pontius.....Controller

Nineteen directors, including one from each of twelve of the member cities and seven from Los Angeles, the thirteenth city.

GENERAL STAFF

F. E. Weymouth.....General Manager and Chief Engineer
J. L. Burkholder.....Assistant General Manager
Julian Hinds.....Assistant Chief Engineer
James H. Howard.....General Counsel
Arthur A. Weber.....Assistant General Counsel
J. M. Luney.....Assistant Controller
J. M. Gaylord.....Chief Electrical Engineer
R. B. Diemer.....Distribution Engineer
James Munn.....General Superintendent
L. V. Branch.....Senior Engineer
Don J. Kinsey.....Assistant to the General Manager

DIVISION ENGINEERS

(Jan. 1, 1933 to Oct. 1, 1938)

W. E. Whittier.....Divisions 1 and 2
R. C. Booth.....Division 1
John Stearns.....Division 3
B. C. Leadbetter.....Divisions 4, 5, and 6
R. B. Diemer.....Division 4
O. J. Schieber.....Divisions 4 and 6
J. B. Bond.....Divisions 5 and 6
Robert N. Allen.....Transmission Division
W. J. Neale.....Maintenance Division

GENERAL SUPERINTENDENTS OF CONSTRUCTION

(Jan. 1, 1933 to Oct. 1, 1938)

R. C. Booth.....Coachella tunnels & Eagle Mountain and Hayfield pumping plants
B. C. Leadbetter.....Coachella and San Jacinto tunnels
B. H. Martin.....Iron Mountain pumping plant
R. M. Merriman.....Coachella tunnels
C. R. Rankin.....San Jacinto tunnel
T. T. Walsh.....Intake and Gene pumping plants

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(January, 1930 to June, 1932)

Thaddeus Merriman
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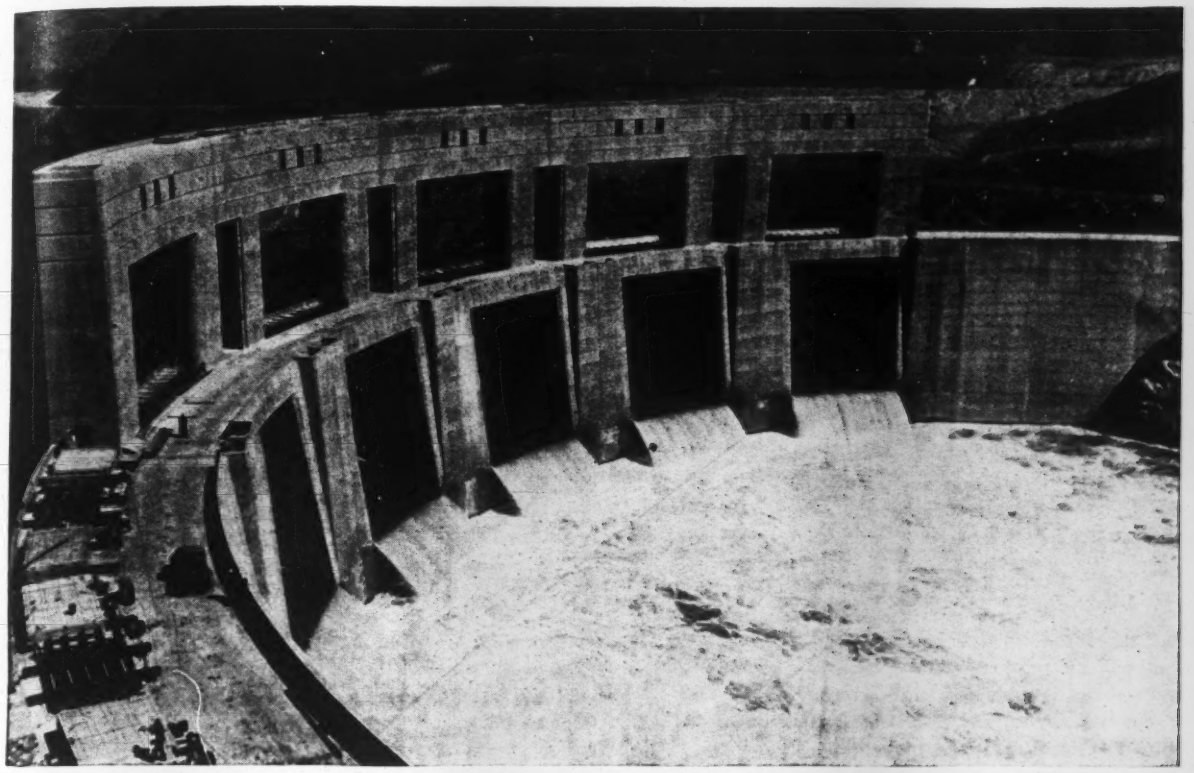


FIG. 1. PARKER DAM ON THE COLORADO RIVER FORMS THE POOL FROM WHICH AQUEDUCT WATER IS PUMPED

Governing Factors in Aqueduct Design

D. B. GUMENSKY,

Engineer, Metropolitan Water District of Southern California

Designs of structural and hydraulic features were developed simultaneously with final location surveys and cost determinations

DESIGNING the Colorado River aqueduct involved two distinct and highly specialized fields. To deliver a water supply to cities of the district it was necessary, first, that the water be lifted from the river to the required elevation and, second, that a conduit be provided in which it would flow to its destination. Design and construction of the mechanical and electrical elements of the pumping plants were under the direction of the chief electrical engineer and are described elsewhere in this issue. Factors governing design of the aqueduct proper and of the distribution system were analyzed in the civil engineering division; these are discussed in the following.

In the early stages of planning, the most important work was the preparation of comparative costs on different routes from various points of diversion. To simplify this work, the principal types of aqueduct construction (tunnel, cut-and-cover conduit, canal, and pressure pipe) were designed for the general conditions of location and for a wide range of sizes. Hydraulic properties and physical quantities involved in 1 lin.ft. of construction were then computed for each of the typical sections and these data, in the form of tables and charts, were supplied to the locating and estimating staff.

As the various routes were projected on maps and on the ground, proper sizes of the aqueduct for the required capacity and for the available grades were readily selected from the charts and tables. Quantities and costs were computed by multiplying the "linear foot" values of the selected sections by the length of each type. This procedure made for rapid and efficient determination of relative costs of the projected routes. Wherever problems of location and construction departed from typical conditions, special studies were made and tentative designs and cost estimates were prepared for each specific case.

As the selection of the routes narrowed down to the diversion at Parker and terminal storage at Cajalco, the designs were fitted more closely to the character of the terrain traversed and to the actual con-

ditions of location. The selected route then was divided into sections in each of which accessibility, general topography and features of construction were somewhat uniform. For each such section unit costs were determined, based on quantities for a set of tentative sizes. Then unit costs proportional to the sizes of aqueduct sections were analyzed and studies were made of the most economical size to use for each section. These studies were later used in combination to arrive at the final sizes for the entire length of the aqueduct.

Design of each of the typical aqueduct sections was carried to an unusual degree of refinement because each cent saved per linear foot, multiplied by the length of the aqueduct, meant a total saving of $10,000.

Before actual construction was begun considerable experimentation and research had been carried on by the district. Much of this research was essential to efficiency in the use of construction materials under the very adverse conditions that obtain on the desert. Materials quite satisfactory elsewhere proved under test to be wholly inadequate for service on the desert. So many research problems on materials and methods had to be solved that work on them was centered in a testing laboratory built at the field headquarters in Banning. Here a research staff was kept continuously at work for several years.

TABLE I — COMPONENT PARTS OF THE MAIN AQUEDUCT

Type of structure	Length (miles)
Tunnels	92
Cut-and-cover conduit	55
Concrete lined canal	63
Inverted siphons	29
Delivery pipe lines (pump stations)	1
Open waterways in reservoirs	2
Total, Intake to Cajalco Reservior.	242

TABLE II — ROUGHNESS COEFFICIENTS OF DIFFERENT TYPES OF CONSTRUCTION

Type	Value of "n"
Concrete lined open canals	.014
Concrete cut-and-cover conduit and tunnel lining, with steel forms	.013
Concrete siphons cast in place	.013
Precast concrete pipe (poured standing on end)	.012
Welded steel pipe (lined with coal-tar enamel)	.014
Welded steel pipe (lined with centrifugally spun cement mortar)	.012
Centrifugally spun concrete pipe	.012

For example, what cement would best meet requirements in the desert where concrete had to be placed under conditions extremely adverse to curing as well as to long service? An elaborate series of tests under desert conditions led to selection of a "modified portland cement", and this is giving very satisfactory results. Again, the scarcity of water led to tests with actual exposures on the desert of surface sealing compounds for curing exposed concrete. Many patented preparations were rejected and decision was reached that, regardless of materials used, single-coat applications would be inefficient. Specifications finally called for two coats of coal-tar cut-back. When this was properly applied it gave excellent protection.

However, a black coating was undesirable. Solar heat absorbed by the black surfaces markedly increased the maximum temperature rise during setting of the concrete and increased ultimate shrinkage. A corrective was the use of whitewash over the tar. This expedient was found to decrease maximum temperatures 20 to 30 deg. F.

Before making final choice of design, specimen siphons and a length of cut-and-cover conduit were actually constructed on the aqueduct line, were backfilled and tested for stresses and deformations. The results led to certain modification in designs and eventually to the large program of record-size precast concrete pipe in the distribution system.

A great deal of time and effort was expended in developing coal-tar and mortar lining suitable for being spun into large steel pipes. Similarly many other questions, not of great individual importance perhaps but adding up to a formidable total, were answered in a highly effective way by carefully supervised experimentation.

The most ambitious and important research program related to pump

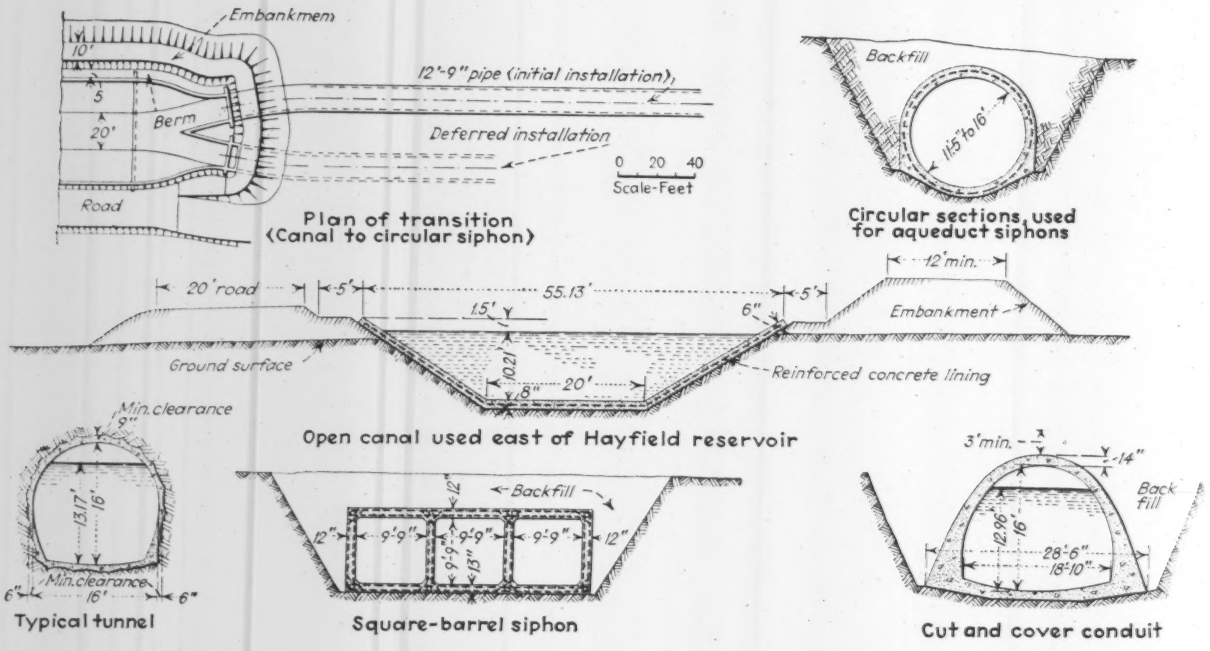


Fig. 2. These sections were used for 99 per cent of the total 242 miles of main aqueduct.

design. When aqueduct studies were begun the expectation in the matter of pump efficiency was about 85 per cent, and it was thought that for the sizes involved (about 200 sec.-ft. per unit), double-suction horizontal pumps would be required, with double-stage for the higher lifts.

The importance of obtaining the highest possible pump efficiency is apparent from the fact that for each per cent it could be increased there would be a saving of $50,000 per year in the cost of power. Also, simplification of pump form meant large savings in installation costs. Careful experimental study was evidently justified, and a special laboratory was accordingly set up at the California Institute of Technology in Pasadena. Here a thorough investigation of the district's pumping problem was carried on cooperatively by the district staff and members of the institute faculty, with valuable assistance from pump manufacturers. The result is an efficiency expectancy of 92 or 93 per cent with single-suction, single-stage vertical units for all lifts up to the maximum of 441 ft. The resultant savings make the $150,000 cost of the research program seem insignificant: power savings alone will be $350,000 per year.

Diversion and headworks

Diversion of Colorado River water will be made at the intake pumping plant on the west bank of Parker Reservoir about 2 mi. upstream from Parker Dam. This dam is a concrete arch structure 315 ft. high but with only about 70 ft. difference between upstream and downstream water levels. Low effective height is due to the unusual depth of excavation below the normal riverbed, made necessary by the depth of debris in the river channel (*ENR*, Nov. 25, 1937, p. 853).

Five 50x50-ft. stoney gates provide for the passage of the maximum stream flow expected. Each gate is manually controlled and is operated by a small electric motor; gate operation will be such as to maintain the surface level in the reservoir at El. 450. The maximum capacity of the gate openings is more than 200,000 sec.-ft. These gates impose heavy cantilever stresses on top sections of the arch, which had to be designed accordingly. The primary function of the dam is to regulate and clarify the flow of the river rather than to elevate the water. Height of the dam was limited not by structural considerations but by the location of the city of Needles, Calif., at the headwaters of the reservoir, and by the elevation of the Santa Fe Railroad which crosses the river at Topock, Ariz.

The dam was designed and built by the U. S. Bureau of Reclamation with funds furnished by the district. Dam and reservoir will be the property of the government and will be

TABLE III — HYDRAULIC PROPERTIES FOR TYPICAL AQUEDUCT SECTIONS SHOWN IN FIGURES 2 AND 3

Main Aqueduct	Size (ft. in.)	A	V	Q	r	n	s
Open canal	20 – 0	360.57	4.45	1,605	6.35	.014	.00015
Cut and cover conduit (East of San Jacinto)	16 – 0	223.43	7.18	1,605	5.10	.013	.00045
Cut and cover conduit (West of San Jacinto)	15 – 4½	206.20	7.80	1,605	4.90	.013	.00056
Tunnel (East of San Jacinto)	16 – 0	119.11	8.40	1,605	4.89	.013	.00065
Tunnel (West of San Jacinto)	15 – 3	172.60	9.30	1,605	4.66	.013	.00085
Concrete siphon							
Single barrel	16 – 0	201.06	7.98	1,605	4.00	.013	.00077
Double barrel in canal	12 – 9	127.67	6.29	802.5*	3.19	.013	.00065
Double barrel in conduit	12 – 4	119.47	6.72	802.5*	3.08	.013	.00077
Whitewater	11 – 5	102.43	7.83	802.5*	2.85	.013	.00119
Precast pipe	12 – 0	113.10	7.15	802.5*	3.00	.012	.00077
Three square barrels	9 – 9	94.56	5.65	535.0*	2.50	.013	.00072
Distribution System							
Precast concrete pipe	12 – 8	126.01	5.95	750*	3.17	.012	.00050
	9 – 8	73.39	6.94	509*	2.42	.012	.00097
Steel pipe	11 – 6	103.87	7.22	750*	2.83	.014	.00113
	9 – 8	73.39	10.22	750*	2.42	.014	.00286
Circular tunnel	10 – 0	78.54	6.48	509*	2.50	.013	.00095

*Capacity with one barrel.

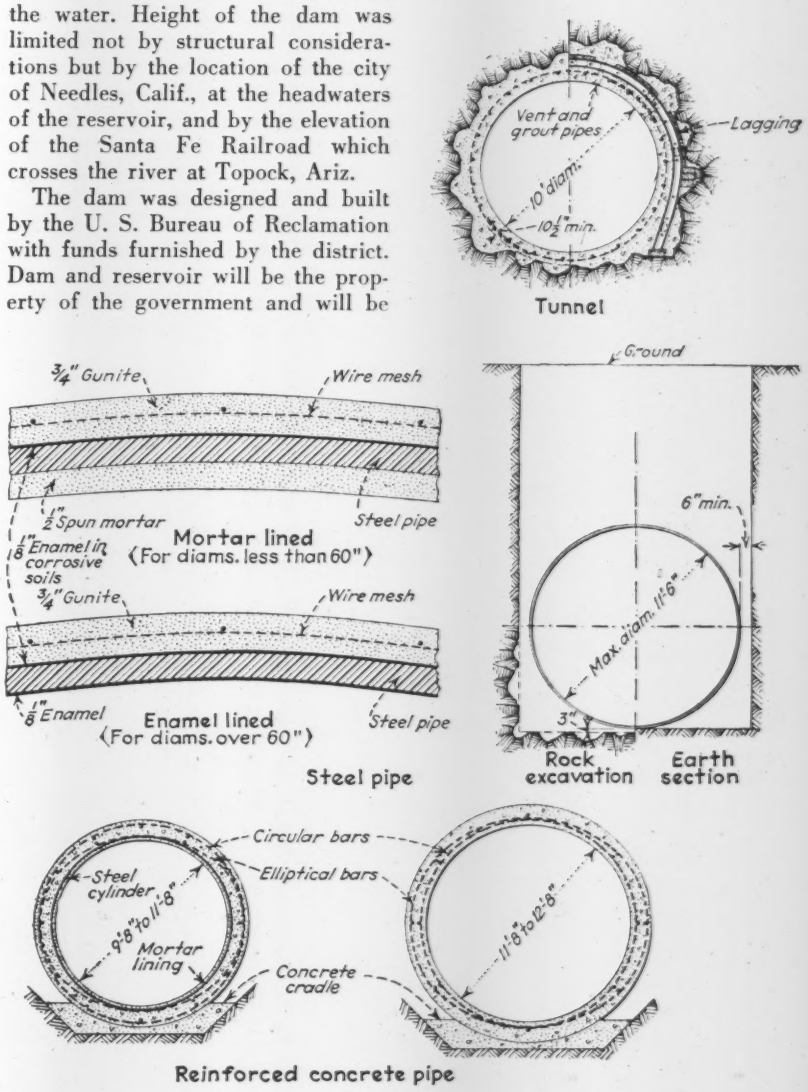


Fig. 3. Types of structures designed for pressure in the distribution system.

operated by it for the benefit of the district. The government retains one-half the power privilege at the dam and a limited right to regulate the top 10 ft. of storage in the reservoir. The remaining one-half of the power privilege belongs to the district.

This joint arrangement was desirable because parts of the dam are in two states, California and Arizona, and a federal organization, such as the Bureau of Reclamation, had a more convenient and effective way of dealing with authorities of the other state than the district had. The work was, in fact, delayed and construction of the dam was suspended for months by legal controversies with the state of Arizona which claimed, among other things, that no Congressional authority for the construction of the dam existed. This alleged deficiency was corrected by specific provision for Parker Dam in the rivers and harbors bill passed by the 73rd Congress and approved by the President Aug. 30, 1935.

The intake pumping plant will lift the water 291 ft. and will discharge via tunnel into Gene Wash reservoir. Gene pumping plant has a lift of 303 ft. and will deliver through two short tunnels and a siphon into Copper Basin reservoir. From here the flow into the first long section of the aqueduct will be regulated by gates operated through remote control.

These two small reservoirs are created by concrete arch dams of very slender section, designed by using a trial-load method of analysis for a maximum stress of 500 lb. per sq.in. The analyses allowed for the effects of (1) tangential shear between adjacent arches, (2) twist in vertical blocks and (3) foundation deformations. To reduce the effect of temperature drop, concrete in both dams was designed to be cooled to an average of 50 deg. F. prior to grouting contraction joints, which were spaced 50 ft. apart.

Tunnels a major item

Tunnels constitute a large proportion of the aqueduct length and about 60 per cent of them pierce mountains lying directly across the route. The most notable of these are the 18.30-mi. East Coachella and the 13.04-mi. San Jacinto tunnel through the final barrier between the desert and the coastal watershed.

The cross-section of the typical tunnel is the conventional horseshoe shape lined with plain concrete, and with invert curvature flattened for convenience in construction. Where the soil is yielding or where large external pressures may develop, curvature of the invert arch was increased to a radius of 16 ft. to improve its ability to carry such loadings. Where excessive loads were expected, reinforcing steel was added. Elsewhere, when economical and structurally advantageous, the required strength was achieved by thickening the plain concrete lining and by consolidating the surrounding rock with cement grout forced into the cracks and openings in the rock. This practice was developed to a high degree in San Jacinto tunnel (*ENR*, May 7, 1936, p. 661).

Sizes of the various tunnels were selected to give maximum overall economy of construction and operation in each case. Then, to avoid undesirable multiplicity of sizes and to simplify construction, all tunnels were grouped in two optimum average sizes. From the Colorado River to San Jacinto, inclusive, all tunnels are 16 ft. in finished diameter. The Bernasconi and Valverde tunnels, farther west, have diameters of 15 ft. 3 in. and are placed on a steeper slope to give the same flow. The reduction in size of the latter two gives the greatest economy for the section of the aqueduct between San Jacinto and Cajalco, consisting of tunnel, cut-and-cover conduit and monolithic siphon types in various lengths.

All tunnels in the upper feeder of the distribution system were made strong enough to carry pressure, either with reinforcing or with thickened concrete. Circular sections 10 ft. in diameter were selected as best for overall economy of construction. Where the excavation is in solid rock with adequate depth of cover, the lining is not reinforced; sufficient structural strength and water-tightness are derived from the backing of the rock, which is consolidated by cement grout. Where the distance from the tunnel bore to the surface is less than two and one-half times the head of water on the tunnel, steel reinforcement is used in the lining for full water head. Tunnels in alluvial sand and gravel are reinforced against both internal and external loads.

Open canals were cheapest

Open, concrete-lined canal construction is predominant in the desert between the Whipple Mountains and Hayfield. This is least expensive of all conduit types and requires the least head for a given velocity. It has the disadvantage of being subject to damage from floods of cloudburst proportions, but is expected to be safe in the smoother locations where cross-drainage problems are simple. The section is set well down into the ground, to give security, and is protected against flood damage by an

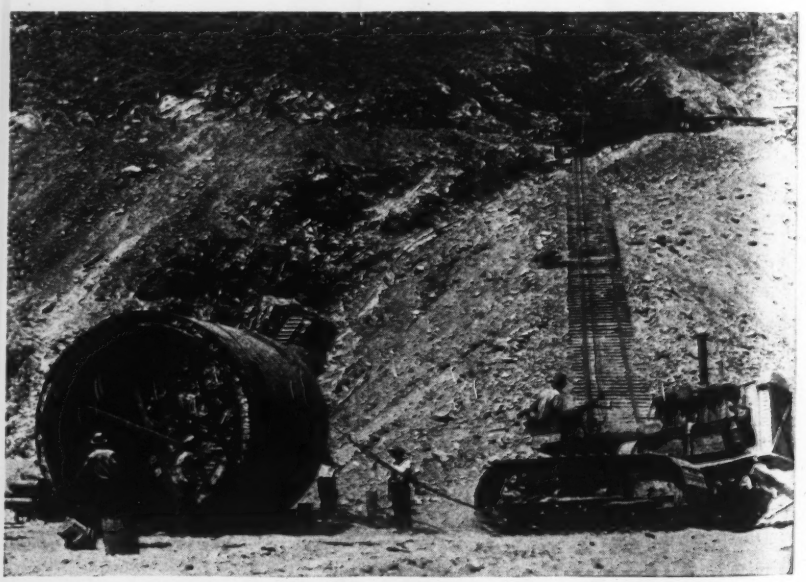


Fig. 4. Record size precast concrete pipe being rolled into place by a tractor.

Fig. 5. Assembly of reinforcing steel for Eagle Mountain siphon.

ample system of training ditches and other drainage works.

The concrete lining varies from 6 to 8 in. in thickness and is continuously reinforced with high elastic-limit steel, equal to ½ of 1 per cent of longitudinal concrete area and ¼ of 1 per cent of the transverse area. To reduce spacing and size of shrinkage cracks, the strength of concrete was specified not to exceed 2,500 lb. per sq.in. The section of the canal was made smaller and set on a steeper grade than the economic studies indicated. This was done to achieve, for full flow, a velocity of 4.45 ft. per sec. which is sufficient to insure the transportation of blow sand or light debris to the sand traps and settling basins provided for their removal.

Cut-and-cover design details

Cut-and-cover conduit is used across the desert areas, where open canal is not permissible, and for surface lines west of Hayfield that are not under pressure. The standard section employs plain concrete placed in forms in an open trench and then backfilled. It consists of two parts; the upper arch and the invert which sometimes acts as an inverted arch. The arch is proportioned to resist the external loads imposed upon it; its abutments are flared to provide a sufficient bearing area and to keep the thrust line within the middle third of the section under varying loads.

In cuts through solid rock, flaring of abutments was not necessary and considerable savings in excavation and in concrete were effected by using a more slender section poured directly against the sides of the trench. For yielding foundations, excessive depths of cover and locations under highway or railroad, a heavy reinforced section was designed for each specific condition. In the plain, normal section, contraction joints of two types were put in at 35-ft. intervals. Construction joints at the ends of separate pours are plain butt joints painted with coal tar and made watertight by a $\frac{3}{16}$x8-in. steel waterstop, also painted with coal tar and extending 1 ft. higher than the normal water surface. Dummy joints, likewise set at 35 ft. but midway between the construction joints, were embedded in concrete during placing. They consist of similar $\frac{3}{16}$x8-in. steel waterstops to which fins of lighter plate were welded at right angles. These fins, also painted with coal tar, extend to the top of the arch. The purpose of the joints is to confine shrinkage cracking to sections where waterstops will prevent leakage.

Siphons and protective works

The crossing of drainage channels, ravines and other depressions along the aqueduct route required the use of inverted siphons. There are 144 such structures on the main aqueduct ranging from 175 to 26,400 ft. in length, and from a few feet to a maximum of 153 ft. in operating head. These siphons were all built of reinforced concrete. The most predominant construction consists of two parallel circular barrels, generally used wherever the length is more than 400 ft. or where the operating head exceeds 25 ft. Only one barrel of these siphons was built, leaving the second to be added when required.

Where the siphons are short and the head low, the advantages of double-barreled construction are outweighed by the additional cost of the more complicated end structures, and a single circular barrel or a rectangular three-compartment type is more economical. Siphons of the latter type provide an artificial waterway for cross-drainage in flat country traversed by canal where storm runoff is of the so-called sheet-drainage type. Drainage ditches running diagonally to the canal intercept the sheet runoff flow and convey it to the places of concentration at and over the low-head siphons. These siphons are spaced at intervals determined by the character and the size of the area contributing to the runoff.

Pressure pipes in the distribution system are either precast reinforced concrete or welded steel. Precast concrete pipe (*ENR*, June 11, 1936, p. 852) is used for heads under 300 ft., while steel pipe (*ENR*, May 20, 1937, p. 747) is used predominantly for heads over 250 ft.

Except at the pumping plants, there is little occasion to control the flow between the intake and Cajalco reservoir, hence special structures are not numerous. Wasteways, controlled by radial gates and capable of diverting the entire flow into natural drainage channels, are provided at intervals. Overflow and siphon spillways, or other automatic devices, at each pumping plant, provide means for discharging the flow in the event of interruption in pump operation.

Although the open canal is well protected by drainage ditches and

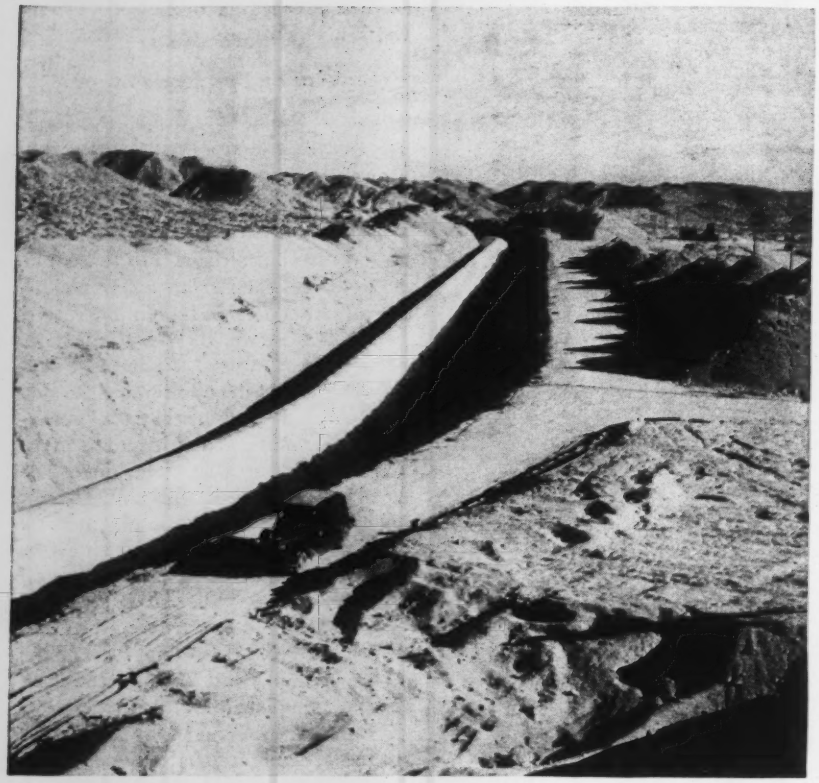


Fig. 6. A typical section of completed cut-and-cover conduit along the main aqueduct ready for placing the backfill.

dikes, it is possible that limited surface flows may be intercepted during heavy storms. To prevent dangerous accumulation of such flows, paved depressions in the canal banks were put in at intervals, somewhat similar to the standard "dips" on secondary western highways. Sand traps and settling basins are provided along the open canal sections at intervals believed to be consistent with removal requirements.

Hydraulic features

Friction losses in the entire aqueduct were computed on the basis of Manning's formula:

$$V = \frac{1.486}{n} r^{\frac{2}{3}} s^{\frac{1}{2}}$$

where V is the velocity of water in feet per second, n is the coefficient of roughness, r the hydraulic radius of the channel, and s the hydraulic slope. Use of the Manning formula was decided upon after careful study and comparison with other formulas, particularly Hazen & Williams, and Scobey, for flow through pipes, and with Kutter for flow in open channels. The Manning formula has special advantages in economic studies requiring differentiation or integration of mathematical expressions involving the velocity of flow. Values selected for the coefficient of roughness n for the various types of construction are given in Table II.

The grade tunnel and the cut-and-cover conduit were designed for depths of flow that give the same discharge as when flowing full, thus avoiding any danger of "choking" the aqueduct. The velocities in these sections were selected in conjunction with slopes and sizes to give the minimum overall cost. Open canal was built on a somewhat steeper slope and of smaller size than the economical studies indicated.

To the friction losses in pressure pipe were also added losses caused by bends; computed thus:

$$h = 0.25 \frac{V^2}{2g} \sqrt{\frac{D}{90}}$$

in which h is the head, in feet, lost in a given bend; D is the angle of bend in degrees; V is the velocity in the pipe in feet per second. All bends in concrete pipes have a radius of at least two and one-half diameters of the pipe. In the steel pipe, for fabrication reasons, sharper bends are permitted. At all changes between grade conduits and pressure pipes, also between various types of grade conduit, transition structures have been designed to allow a smooth change from one shape and velocity to another. Transitions requiring an increase in velocity were allowed a loss equal to 0.1 the change in velocity head: transitions involving recovery of the velocity head were allowed a loss equal to 0.2 change.

Specifications and contracts

Plans and specifications for the construction of the aqueduct were prepared in coordination with the program of construction. Since the distances between access points for the San Jacinto tunnel were greater than for any other on the project, the time required for driving this tunnel would determine the earliest possible date for completing the entire aqueduct. Hence this tunnel was the first feature of the aqueduct proper on which bids were invited. However, the award of contract was delayed 4 months until Mar. 13, 1933 because of inability of the low bidder to meet bond requirements.

As an aid in relieving the acute unemployment situation existing at that time, the construction of the Coachella group of tunnels by district forces was authorized on Dec. 21, 1932. Specifications for other main aqueduct tunnels followed until, by the end of 1933, all had been advertised. Bids on construction of tunnels in the distribution system were first called for in the latter part of 1934. Specifications for the first surface work on the main aqueduct were issued in 1934 and on the distribution system in 1935. Some remaining units of the distribution system are being designed at the present time to be advertised for construction in the near future.

In the preparation of specifications, the aqueduct was divided into a number of construction units or schedules. Each schedule was such that the amount of any one contract would not exceed the usual financing ability of a competent contractor in this line of work. The majority of the schedules amounted to about $1,000,000 each. Contractors who were able to do so could bid on several schedules at the same time; sometimes contracts with one firm covered as many as four complete schedules simultaneously.

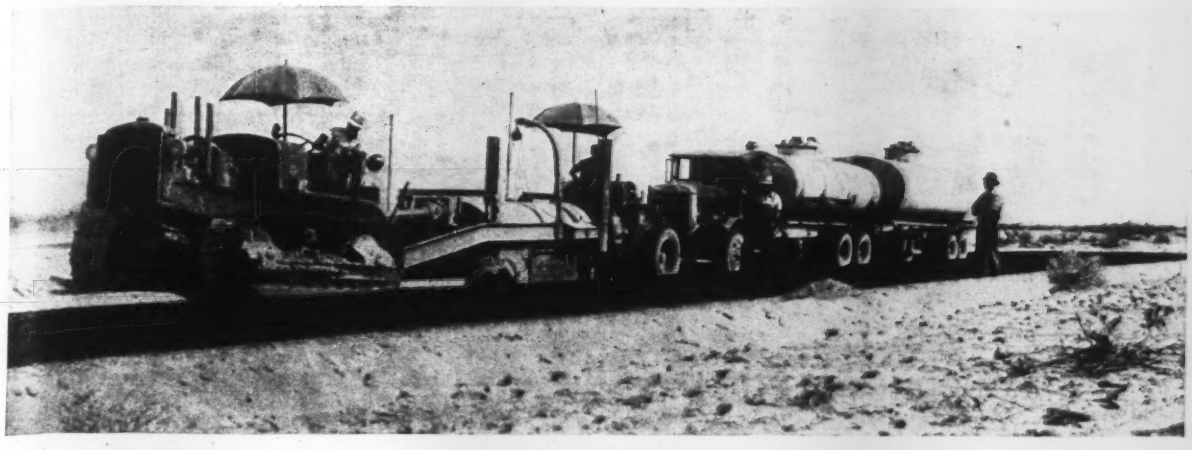


FIG. 1. ROAD-MIX EQUIPMENT PUT ASPHALTIC SURFACING ON CONSTRUCTION ROADS AT THE RATE OF A MILE A DAY.

Construction Program and Management

J. L. BURKHOLDER

Assistant General Manager Metropolitan Water District of Southern California

Unusual problems incidental to operating on the desert; training inexperienced men and meeting difficult conditions were all part of the job

WHEN the "order to proceed" in building the Colorado River aqueduct came in December, 1932, only devious wagon trails existed along most of its 242-mi. length. The final location traversed wide valleys and rugged mountains of a barren, parched desert where little or no water was to be had and high temperatures prevailed for more than half the year. Some 200 mi. of the route was remote and difficult of access. Definite engineering plans had been completed and finances were arranged, but a major undertaking yet remained in providing the water, roads, power and communication facilities which had to be available before the real construction job could start.

The construction program adopted by the district at the outset planned on completion of the entire aqueduct in 6 years' time because this was the time estimated for completing the 13-mi. San Jacinto tunnel. To effect savings in interest cost, certain units of the project were deferred as long as was consistent with a completion date 6 years after the start. This program as laid down by directors of the Metropolitan Water District embraced the following broad policies:

(1) Necessary construction utilities would be provided by the district.

(2) The Coachella tunnels and adjacent surface work would be constructed by force account.

(3) Bids would be taken, by construction schedules, on all other main tunnels.

(4) Other units of the aqueduct would be scheduled and advertised for bids from time to time as required to meet the fixed completion date.

The decision to construct about one-third the tunnels and a small part of the surface work with district forces was reached after careful study of many factors, including the steadily increasing need for employment. Force account work would (1) provide earlier employment for 1,500 local residents, (2) stimulate local enterprise through immediate purchase of several hundred thousand dollars worth of materials and supplies and (3) effect savings in cost. There were also intangible benefits such as demonstrating the ability of local labor, establishing a precedent for construction methods, safety, care of the workmen and wage scales. With reasonable costs of construction established by force account work, competitive bidding for the work to be done by contract would be stimulated. Due to the immediate availability of trained crews thus provided, there would be insurance against delay in completion time if the work of any contractor had to be taken over by the district. Execution of this

TABLE I — CONDENSED CONSTRUCTION SCHEDULE

Feature	Date Started	Date of Completion
Construction utilities	Oct., 1932	Dec., 1933
Tunnels (29, totaling 92 mi.)	Jan., 1933	*June, 1939
Diversion and auxiliary storage	Oct., 1934	Apr., 1938
Conduit, canals and siphons (146 m..)	Nov., 1934	June, 1938
Pumping plants (5, total lift 1,617 ft.)	Oct., 1935	Dec., 1938
Transmission lines (237 m.)	Oct., 1935	Jan., 1938
Terminal storage (100,000 acre-ft.)	July, 1935	May, 1938
Distribution system and feeders	Feb., 1935	

* Estimated.

program has given gainful employment to about 35,000 persons; the number reached a peak in May, 1937, with a total of 10,781 employees of the district.

Confronted with the problem of controlling and directing 28 major contracts and extensive force account operation along a 242-mi. desert construction front, district engineers planned specifications and provided an organization that would insure a uniformly high standard and quality of work. Necessary preliminaries to attaining these objectives were:

(1) Locate and investigate the quality of all aggregate deposits along the route.

(2) Establish a testing laboratory and program its research and routine work.

(3) Test proposed designs and construction methods in advance of starting construction by actually building short test lengths of each type.

(4) Secure uniform interpretations of the intent and meaning of the specifications by engineering supervision and adequate detailed inspection.

Little or no concrete work had ever been done along most of the aqueduct route, hence there were no proven sources of sand and gravel. Prospecting the surface and digging test pits located some 60 deposits. Various concrete mixes were prepared with materials from all of these and were fully tested for workability, strength and permeability. Based on these tests, final specifications provided for using these deposits after the necessary processing to reduce fines to a maximum of 9 per cent.

Removing the fines by the usual washing methods was not possible due to the limited water supply, hence means for doing this by drawing air through a curtain of falling sand had to be developed. The district's Wide Canyon aggregate plant, designed in 1934, pioneered the first air cleaning equipment. Contractors followed by building "home-made" air equipment for sucking out fines. These early plants were generally unable to fully attain the desired degree of cleaning. Manufacturers became interested and improved or developed equipment so that satisfactory results could be obtained with air whereupon its use became general. The average materials along the route had an excess of fines, usually 10 to 18 per cent that would pass a 100-mesh screen. With the improved air cleaning equipment this excess of fines was reduced to a final content of 6 to 9 per cent.

Prior to commencement of the general program of surface construction, district forces constructed the 790-ft. Fan Hill siphon and the adjacent 390 ft. of conduit with connecting transitions in order (1) to check the practicability of specifications tentatively prepared for surface construction and (2) to develop and demonstrate construction methods and equipment.

At the same time, bids were taken for construction of the 719-ft. length of the 12-ft. Little Morongo siphon which was constructed of precast pipe. Thus there would be a basis for comparison of practicability and economy of the two types. The precast siphon, designed to operate under a

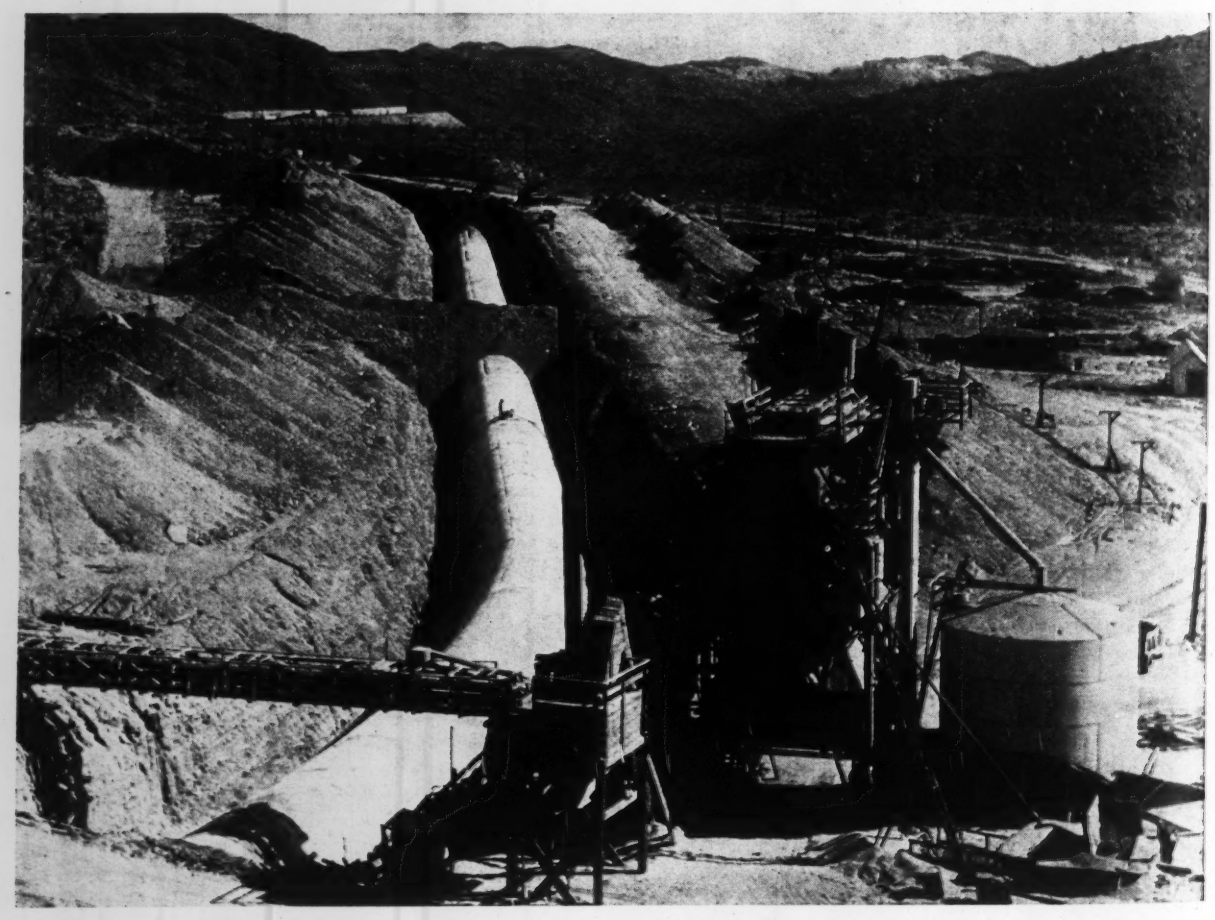


Fig. 2. Typical concreting plant along the cut-and-cover sections of the aqueduct.

maximum head of 118 ft., is believed to be the first precast pipe of this diameter. It proved uneconomical for the main aqueduct but was adaptable to and later was used under conditions prevailing on the distribution system where rights-of-way were restricted and terrain more uniform.

These field tests provided much valuable information and served as training schools for engineers and inspectors who later supervised construction on a larger scale. Information obtained brought about many improvements in final specifications and in the details of design and construction procedure; circular siphon sections were altered in exterior shape with saving in concrete volume, the curing procedure was perfected, aggregate sizing was coordinated with reinforcement and form requirements and improved form design were made possible.

Engineering supervision

Direct engineering control of construction on the main aqueduct was exercised by five division engineers and their staffs supervising work on six divisions of the aqueduct. The testing engineer was an advisor on all matters pertaining to quality of concrete. During the period of greatest activity the field engineering forces numbered 300.

Due to the extent of the work and the speed of operations, usual methods of keeping track of progress through weekly and monthly reports proved inadequate and were supplemented by telephone reports to field headquarters each morning from as many as 63 jobs. In this manner the assistant general manager was kept currently informed on all details of the work. The data were used for comparing actual and anticipated progress so that it was possible to give warnings in advance of any great delinquency in progress and, where necessary, to give engineering and construction advice and assistance.

At the peak of construction 160 inspectors were required. Because of the necessity for drawing these from local sources, many inexperienced men had to be taken on. A school for inspectors was therefore established to give intensive instruction in concrete technology and the intent and meaning of the specifications. As an aid to class work and for use of field men generally, a printed manual for

Delivering Materials in the Desert

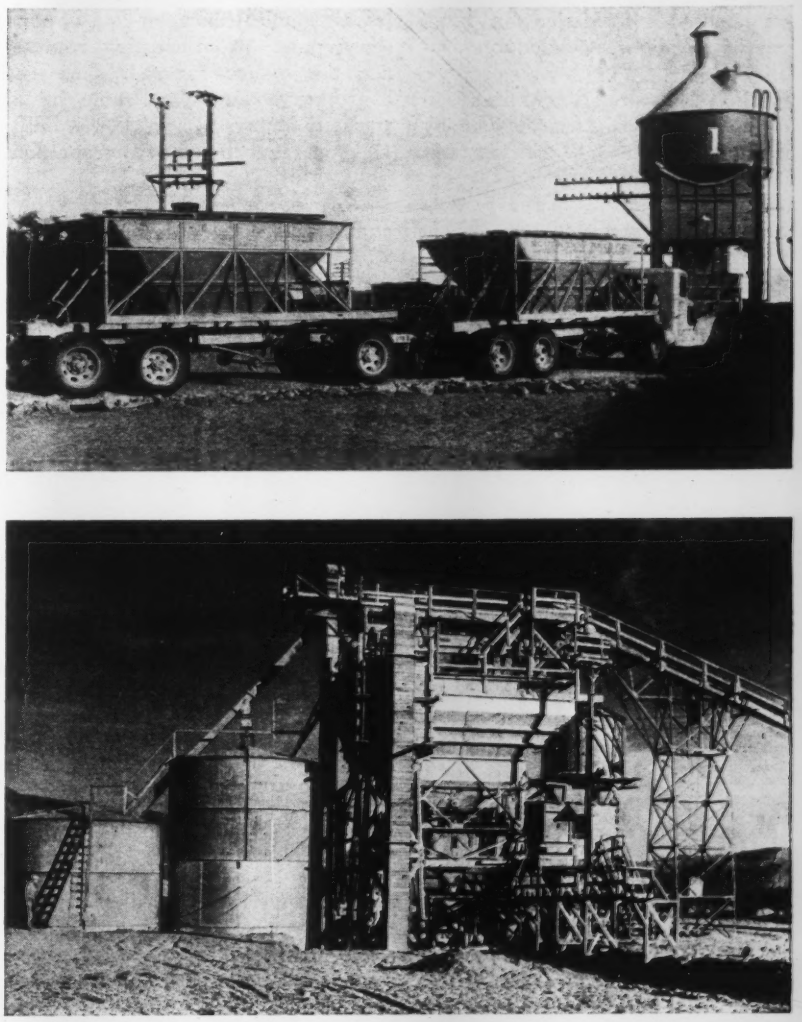


Fig. 3. Bulk cement was hauled from central storage bins in specially designed truck (top) to batching plants in the desert (center) where batch trucks (bottom) took four batches to the mixers on the job.

concrete inspectors was issued containing the standard specifications and detailed information on functions of the district's field organization.

Uniform interpretation of the specifications was further promoted by monthly meetings of division and resident engineers with the testing engineer and the assistant general manager. At these meetings problems arising on the job were discussed, difficulties were analyzed, remedies outlined and, when necessary, recommendations were made to the chief engineer for effecting uniform interpretation of specifications. These efforts toward uniformity not only resulted in a superior quality of work but kept the number of claims resulting from the execution of the contracts to a remarkably low figure. This despite the fact that several contractors worked under as many as four division engineers.

Construction utilities

The decision to build and operate the utilities before actual construction began arose from the belief that large savings would result if these essentials were already available to contractors at stated rates when bids were invited. Building the utilities in advance eliminated certain hazards inherent to remote construction work on the desert and thus reduced the contractors' bidding prices. Resultant cost savings are believed to be far greater than the actual cost of providing the utilities.

The building of 150 mi. of surfaced highways across the desert in an elapsed time of 180 days is worthy of mention. The main construction roads were given an oil-treated wearing surface applied under two classifications, both of which have a 3-in. minimum thickness and are 20 ft. wide. In one type, selected materials were used both for the oil mix and for the 22-ft. sub-base. The second type used natural roadbed material for the sub-base, and either native road material or a combination of this material with crushed stone for the oil treatment. After 5 years of heavy traffic these roads are still in excellent condition. Maintenance costs have been low, averaging about $12 per mile per month.

Electrical energy for construction might have been obtained from individual power plants located on the several parts of the work. After careful study, however, this was found less economical than the plan to purchase power from existing sources near the westerly end of the line and distribute it along the route by a transmission system which was built and operated by the Metropolitan Water District.

No telephone lines were available and the district was obliged to construct a complete telephone system including five telephone exchanges for use of the field forces.

The construction water supply uses deep well sources and consists of four independent sections furnishing water all along the line through welded pipe, varying in diameter from 4 to 8 in., laid in trench. There is a total of fourteen wells, 199 mi. of main pipe line, 20 booster pumping plants, 35 tanks and reservoirs and the necessary power line connections and transformers. Potability tests of all water sources were made at two-week intervals throughout the entire construction period.

Tunnel Construction Problems

Twenty-nine tunnels varying in length from 338 to 96,605 ft. comprise the 92.09 mi. of tunnel on the main aqueduct. Of this total, contracts were awarded for 58.35 mi. and 33.74 mi. was scheduled for construction by district forces. The contractor on the 13.04-mi. San Jacinto tunnel, after having excavated 2.37 mi., was seriously behind his program and completion of this work was added to the district's force account program.

The district awarded contracts for the 58.35 mi. of tunnel to thirteen well-known contractors from various parts of the United States. With the exception of San Jacinto tunnel, all tunnels were completed by July, 1937, well in advance of schedule. Tunnel driving was carried on from 60 headings, of which 17 were reached from nine adits with a total length of 11,499 ft. Twelve headings were worked through six vertical shafts totaling 1,677 ft. in depth; four were worked from two inclined adits, one of which was 5,664 ft. long, and 27 were driven directly from their portals.

The rock formations penetrated by these tunnels may be broadly grouped, in order of their prevalence, in five classes: (1) granitic and dioritic; (2) metamorphic, consisting principally of mica schist and gneisses with quartzite and crystaline limestone in smaller masses; (3) tertiary sediments, consisting of medium hard, red-brown sandstone conglomerate and breccias; (4) partially consolidated quaternary gravels; (5) compacted alluvium, consisting of sand and sandy clay with some niggerheads and boulders.

With the exception of the tertiary sediments, characteristic of the Whipple Mountain range near the Colorado River, which required very little support, all other formations penetrated required support varying from 25 to 100 per cent of the length. The granitic formations were found to be loosely jointed and to have a tendency to air slack when exposed. The metamorphic rocks were normally closely fractured and most of the "heavy ground" was encountered in these materials. The gravels and other alluvial materials required support throughout, but were usually coherent enough to permit excavating without spiling or breast-boarding.

Numerous dead or inactive faults were encountered with crushed zones

TABLE II — TUNNEL CONSTRUCTION PROGRESS DATA
(EXCLUSIVE OF SAN JACINTO TUNNEL)

Excavation		
Average advance per shift — dry tunnels	7.04	ft.
Average advance per shift — wet tunnels	3.4	ft.
Average advance per round (entire aqueduct except San Jacinto)	7.3	ft.
Record daily advance — 3 shifts, single heading	55.	ft.
Per cent of total tunnel length supported	61.9	per cent
Timber support	25.9	per cent
Timber lagged steel support	24.2	per cent
Metal lagged steel support	11.8	per cent
Per cent of tunnel length coated with shotcrete	12.5	per cent
Average amount of explosives used per cubic yard of pay excavation	2.69	lb.
Average power consumption per linear foot of tunnel	203.	kw.-hr.
Concrete Lining		
Average advance of arch lining per shift	55.4	ft.
Average volume of concrete placed in arch lining per shift	179.2	cu. yd.
Average advance of invert placing per shift	267.7	ft.
Average volume of concrete placed in invert per shift	100.5	cu. yd.
Average volume of concrete per linear foot of tunnel — actual	3.72	cu. yd.

varying from a few inches to several hundred feet wide. These zones usually required heavy support and enlargement of the section for extra heavy lining. In the dry tunnels it was unusual to find fault zones extremely difficult. In wet tunnels, however, notably the San Jacinto and the Valverde, water encountered in open seams and in crushed areas gave rise to difficulties that seriously impeded progress.

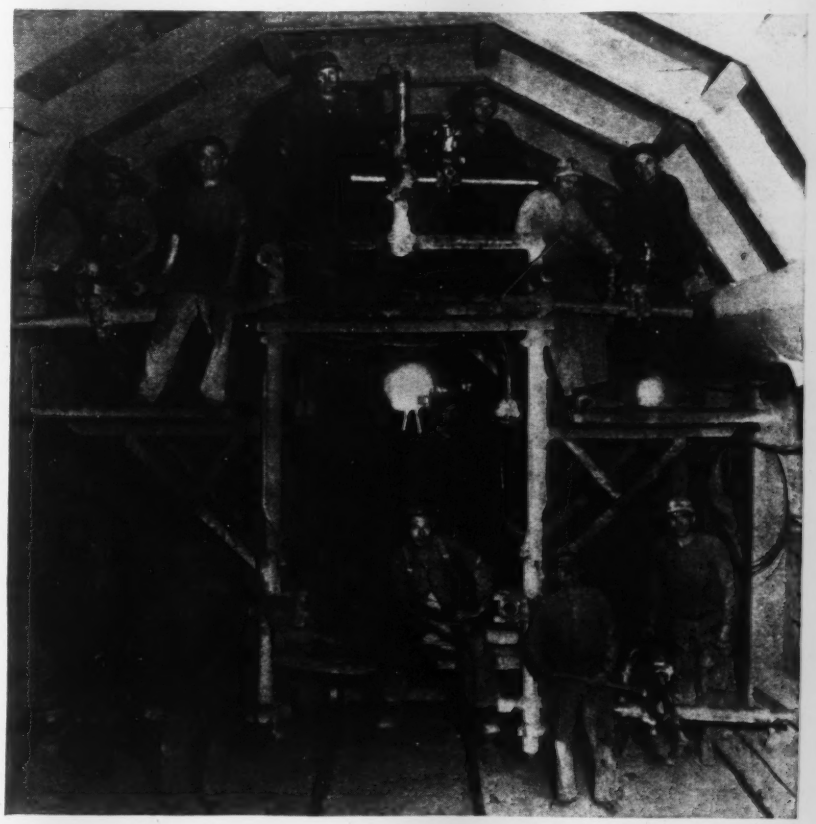
In driving 71.85 mi. of "dry" tunnels, the outstanding over-all average progress of 7.04 ft. per shift or 21.12 ft. per day was attained with maximum monthly advances as high as 1,101 ft. Plant units that were of material aid in attaining this excellent progress were: (1) well designed drill carriages, planned to facilitate full face driving; (2) improved mucking equipment, used in conjunction with large capacity cars and time saving switching devices; (3) automatic-feed drills with longer carriages (30 in.) requiring fewer changes of steel; (4) improved ventilating plants; and (5) the use of standby units to prevent loss of time due to equipment breakdowns.

Profiting chiefly from experience in constructing diversion tunnels at Boulder Dam, excavating plants were designed for the full face method of driving. With the exception of the Whitewater tunnels (in gravel formation) the full face method was ordinarily employed. The only exceptions were in poor rock where the older top-heading-and-bench method or the top-center-drift method was substituted.

Where two headings were operated from a single shaft or adit it was at times possible to use the alternating method of driving to attain maximum economy with crews and equipment. In this method mucking and drilling crews stagger their work at each heading so that mucking is proceeding in one heading and drilling in the other heading. The plan worked well where uniform rock conditions prevailed and no support was required. In so-called "in-and-out ground" the rhythm of this operation is interfered with by timbering operations. This method was employed at the start of work on the East Coachella tunnel but was no longer economical after the headings were separated more than about ½ mi. In the Whipple Mountain tunnel, only 18.7 per cent supported, the method was used with good results from an adit access for a total distance of 15,950 ft.

As an average, each round blasted out of the tunnel headings yielded an advance of 7.3 ft. The average crew required for the various surface and underground operations connected with tunnel excavation numbered 26.5.

Typical drill carriages provided two decks from which the drillers,



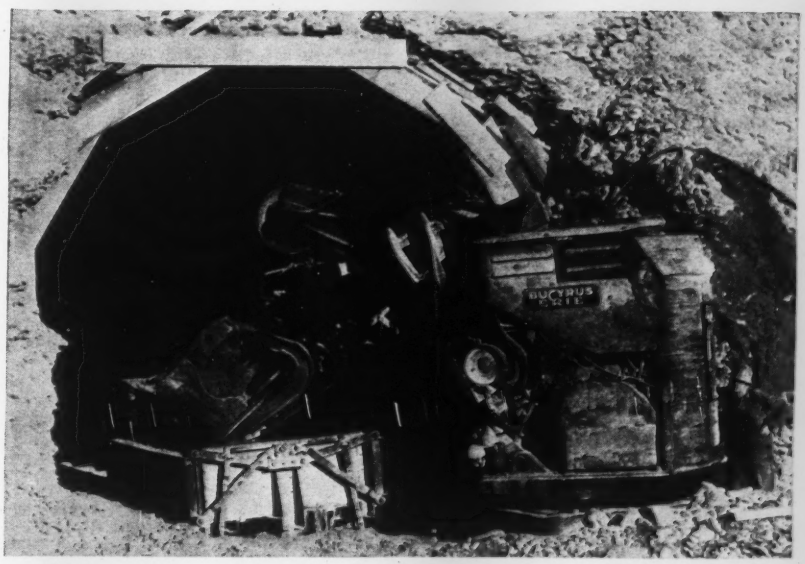


Fig. 4. Specially designed equipment facilitated tunnel excavation. Large drill carriages (top) could mount 11 drills when required. A compact power shovel reduced excavating costs.

by use of swivelled arms and columns supported at the front end of the carriage, spaced and directed drill holes to conform to adopted blasting rounds. From five to eleven drills were thus mounted as required by the rock conditions to drill 25 to 80 holes. The pipe framework of the carriage was used for delivery of air and water to facilitate speedy connections to each drill. The old screw-feed type drills were not used; instead, automatic feed, pneumatic drills were standard equipment because they gave the advantage of constant pressure on the bit, thus permitting maximum drilling speed.

Blasting was done with 40 and 60 per cent gelatin powder (using 1¼ x 12-in. cartridges in distinctive red wrappings) of which an average of 2.7 lb. per cu.yd. of solid rock was used. Some rock required as much as 7 lb. per cu.yd. The powder was detonated electrically from a 440-volt circuit used exclusively for this purpose.

Mucking machines of two types were used: the shovel type and the conveyor type. The latter greatly predominated, although there were five 1¼-yd. crawler-mounted shovels which had been especially designed for this work.

Because mucking machine operation is so frequently interrupted by the switching of muck cars, tunnel men are continually trying to save time by improving the car switching devices. Many new ideas were tried out in the course of this work but the well-known California type switch was the most successful because of its simplicity.

Tunnel tracks built to 36-in. gage with 40-lb. rails were adopted as standard. Traffic protection was provided by automatic or hand-operated block signals at intersections and control points. Power units for haulage were 8-ton battery or trolley type electric locomotives. The all-metal side-dump cars, of either the Western or mine type, were used with capacities of 4 to 6 cu.yd. Excellent ventilation was maintained by surface-operated fans (arranged to exhaust or to blow) through 22-in. metal pipe.

Temporary support

With 62 per cent of the tunnels requiring temporary support, three types were used to suit varying conditions: timber, metal-lagged steel and timber-lagged steel. Shotcrete was put on extensively to prevent air slacking and spalling of the rock; its early application to walls and arch often saved the cost of more expensive supports. It was put on in thicknesses of 1 in. or less at an average cost of $2.40 per linear foot of tunnel—about 11 per cent of the cost of timber support.

Timber supports were five- or seven-segment sets supported by plumb posts; wall plates were used to support arch segments only where bad ground made independent sets unsafe. Timber sizes were 10x10 in. and 12x12 in. for ordinary conditions, or 16x16 in. for heavy pressures.

The metal-lagged steel support consisted of arch ribs supported on wall beams and columns and lagged with pressed steel liner plates bolted to the ribs. In this combination costs were high for both material and labor. Early experiments made by the district led to development of an independent steel rib type of support which effected savings in time and cost. This support, which became standard for the job, consists of two-segment I-beam ribs rolled to proper shape and bolted together at the arch

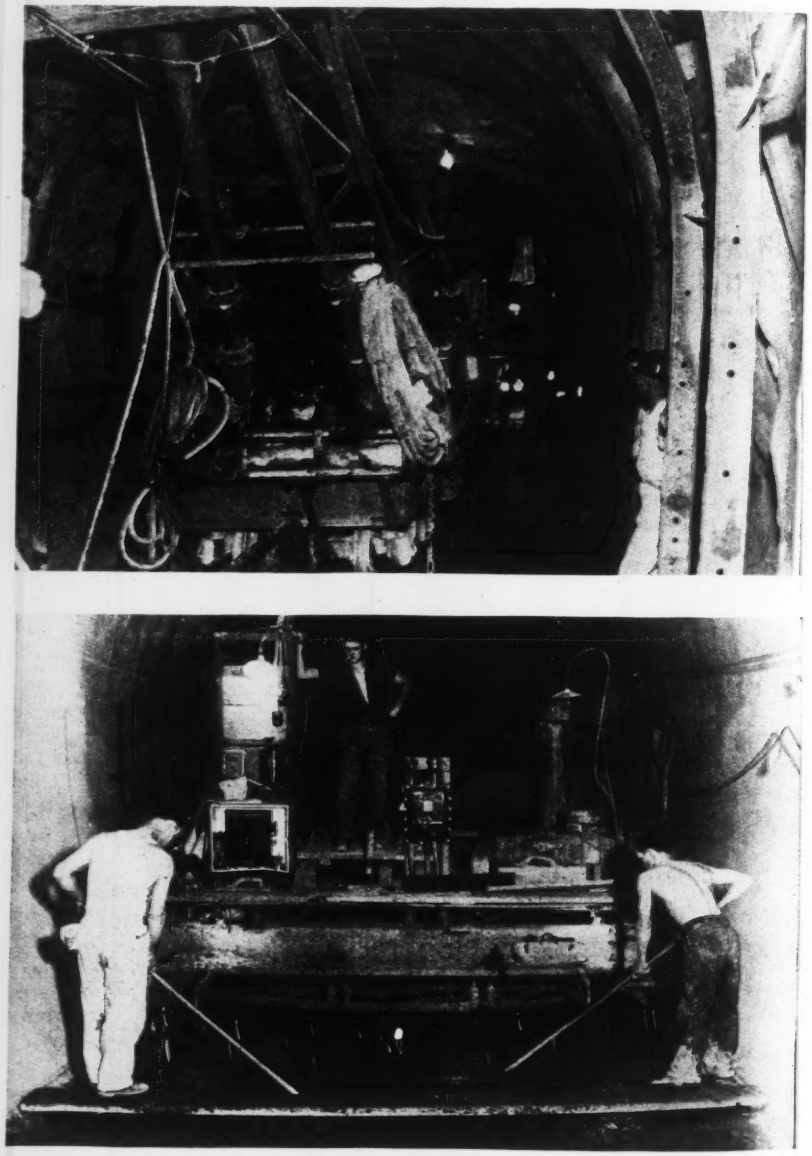


Fig. 5. Concrete was placed in the tunnel arch by five different types of pumps and pneumatic guns. Invert concrete (bottom) was usually placed last, using specially built finisher.

center. Steel rods and timber collar braces are used to bind the sets together.

Concrete lining in tunnels

In most of the tunnels concrete lining was placed by the continuous pour method, utilizing 200 ft. of telescoping steel arch forms, moved ahead in 20-ft. sections as the work advanced. Lining was begun at the point farthest removed from the tunnel access and was advanced toward that point. Concrete was pumped or shot through a single pipe and allowed to flow down the form until side slopes of about 3:1 had been built up and the initial section of the form was completely filled. By moving the discharge pipe laterally, concrete was distributed alternately in the side walls of the arch. The important operation of filling the crown was performed by directing the concrete so as to form nearly horizontal shoulders at the quarter points of the arch, and then subjecting the fresh concrete in the crown section to pressure by keeping the end of the discharge pipe well buried.

In this manner overbroken areas in the crown were filled to heights of 6 ft. or more above the forms. Staggered lines of test holes were drilled in the finished arch to test the filling of voids. Good compaction and smooth surfaces were secured by hand spading the concrete.

Another method, used in lining the Valverde and some other tunnels, was based on placing lining in fixed lengths between bulkheads. This method requires non-telescoping forms of lesser length than needed for the same progress by the continuous method. The construction joints formed at the bulkheads reduce transverse cracking, which was more prevalent in lining placed by the continuous method. Where the daily placement of lining was limited to a length of about 60 ft. all cracking was eliminated. This proved to be a decided advantage especially where it was desired to eliminate infiltration.

Concrete batching plants were located near the tunnel entrance where the weighed materials were placed, dry, in especially designed batch cars for transporting into the tunnel. Water was added at the mixer and the concrete was forced into the steel forms by either a pneumatic placer or a pump.

Five different types of concrete pumps, placers or guns were used on this job with good results (*ENR*, June 18, 1936, p. 876). Most of the yardage was placed with the pumps, which have a higher first cost than the air units, but whose use is believed to have effected an economy in cement because they handle drier concrete.

Pressure grouting behind the lining was employed in several of the tunnels (1) to shut out water which otherwise might build up objectionable pressures on the concrete lining and (2) to increase the strength of the lining in heavy ground. Grout was also used by and at the expense of the construction forces to fill voids back of the lining in lieu of completely filling the voids with concrete in the initial lining operation. No pressure was employed in such cases and sand was usually added to the grout mixture to lower its cost.

Surface Construction Methods

Surface construction, comprising 146 mi. of aqueduct, was completed in the remarkably short time of 2½ years despite the fact that for four months each year high temperatures make it impractical to pour concrete on the desert. This work embraces all conduit, canals, siphons and outlet channels on the main aqueduct. With the exception of one schedule built by district forces, it was done under contract. Bids were taken on 25 schedules with an average length of 6.3 mi. and an average contract price of $1,725,000.

Primary interest in this work focuses upon the ingenuity of the contractors, who designed new equipment and developed improved methods to meet special problems. These developments made possible the contractors' low unit bids and resulted in remarkable records. Concrete placing records on daily 8-hr. shifts over extended periods were: 500 ft. of canal lining, 210 ft. of conduit arch and 200 ft. of 12-ft. 4-in. circular siphon barrel.

On excavation for canal and conduit, in order to shorten the swinging arc and to facilitate the placing of spoil, draglines were used in echelon. A total of 45 machines, ranging in size from 1¼ cu.yd. with 50-ft. booms to 6 cu.yd. with 90-ft. booms were so employed. Preliminary grading and access work was generally done with bulldozers and carryalls.

In conduit work the depth of cut usually varied from 20 to 25 ft. In irregular topography and at tunnel approaches, cuts up to 90 ft. deep were required. For canal section, the depth of cut was considerably less than for conduit and ranged normally from 9 to 12 ft.

Conduit and siphon sections were backfilled as soon as possible in order to protect the concrete during curing. This work, done with draglines and tractor-operated bulldozers, was carried on in such a way as to prevent unbalancing of side pressures against the unseasoned concrete. To improve appearance of finished work and to facilitate drainage, a good job of grading was required over the surface of the backfill and around structures.

Experience on this work improved methods and lowered costs. The last schedules reaped the advantage of earlier experience. The high cost of forms and fully mechanized accessories for such placing, averaging $800 to $1,000 per foot of fixed length of the daily pour, was more than repaid by the lower unit costs attained.

In conduit barrels, concrete was placed in two operations. The invert was placed first, using a mechanically propelled screed somewhat similar to the type used in modern highway construction. The placing of the arch followed with a lag of about seven days to permit the invert to develop sufficient strength to carry the weight of the arch and its forms. The arch section was placed between bulkheads in lengths of 70 to 210 ft. Construction joints were provided with steel water stops and dummy joints were installed intermediately every 35 ft.

Steel forms were required for both the inside and outside surfaces of the conduit arch. Inside forms were twice the length of the outside forms to permit a 14-hr. period of seasoning for arch concrete before inner forms were removed. Inside forms were collapsible and were moved ahead on a jumbo through the forms supporting the currently placed concrete. Outside forms were moved by the self-propelled gantry running on

rails on each side of the invert concrete.

Concrete was batched at central plants, which usually served 6 to 8 mi. of conduit, and was transported either in dry batches for mixing at the placing plant or in a transit mixer which discharged directly on to a belt conveyor delivering to a hopper located above the conduit arch. On the smaller plants the concrete was distributed from the hopper to the forms in hand buggies; the larger units used hopper cars traveling on a track built on top of the outer forms. In either case the concrete was dumped into small movable hoppers connected to elephant trunks which deposited it at the required point without separation. Concrete was placed in level lifts and then vibrated.

Open canal construction

For 62.02 mi. concrete lined canal will carry the flow in parts of the line east of Hayfield reservoir. This total mileage is made up of six locations where regular topography and favorable drainage conditions made canals safe and economical. Divided into nine schedules, five contracting firms did the work in 18 months. The average rate of placing lining was 3.45 mi. per month.

The average unit contract price, exclusive of cement cost, was $5.19 per cu.yd. for concrete 8 in. thick. Since the specified pay lines included only ideal section concrete, means were urgently needed for rapid placing to accurate line and grade. The solution of the problem depended upon the development of highly mechanized plants for trimming the subgrade and for placing the concrete —operations which on previous work had both been done by hand methods. The invention of such machines, developed expressly for this job, and used ultimately by all contractors, resulted not only in excellent progress but also in improvement of the quality of the lining. (See *ENR*, Feb. 20, 1936, p. 279.) Special credit for this development goes to Clyde W. Wood.

The many construction joints, common to canal linings placed by the older methods, were eliminated.

Because the terrain crossed by the canals is flat and has no well defined natural drainage channels, protection was required against the runoff from the occasional torrential rainfall. Siphon crossings therefore were put in under waterways at frequent intervals and levees were added along the upper bank of the canals where necessary. Additional protective works consisted of diagonal and parallel drains to divert surface runoff to the siphons.

In construction of the siphons, complicated form work was required for the 288 transition structures connecting them with canal and conduit sections. More than one hundred of these transitions were designed for double barrel siphons, but one side was bulkheaded for later construction and only one barrel was built initially.

Main aqueduct dams

Located within a few miles of the intake, Gene Wash and Copper Basin dams impound the aqueduct flow in small natural basins located between tunnel portals, thus making connecting structures unnecessary.

The dams at Gene Wash and Copper Basin were built concurrently with Parker Dam by one contractor, thus making use of aggregate deposits and camp facilities developed for Parker Dam.

Parker Dam is known as the "deepest dam in the world" because its foundation extends 245 ft. below the river bed. Its construction is notable because of the bold design of the cofferdams and the excavation methods employed to expose the bedrock. Although the dam will impound water to a depth of but 80 ft., the structure is 383 ft. high from foundation to the top of the control gate house (*ENR*, Nov. 25, 1937, p. 853).

Following the precedent set at Boulder Dam, the Gene Wash and Copper Basin dams are believed to be the first instances in small dam construction, of artificial cooling as a means of contracting the concrete mass praparatory to grouting construction joints. Built in narrow rocky gorges, these dams are variable radius arches extending 138 and 210 ft., respectively, above bedrock. Their construction required 16 months although mass concreting was completed in 6 months.

Gene Wash Dam was cooled to an average temperature of 50 deg. F. by pumping refrigerated water through cooling coils, placed horizontally at 5-ft. intervals throughout the dam. Grouting was accomplished by introducing cement grout simultaneously at the bottom of each contraction joint so that the level of the grout was maintained at equal elevation and was forced from the bottom upward as the operation progressed. Pressures of 65 lb. per sq.in. used at the bottom of the dam were gradually decreased to 25 lb. at the crest. Throughout the procedure the position of the dam was carefully checked for radial and axial deflections. No radial deflection was recorded and the axial deflection was only 0.01 ft.

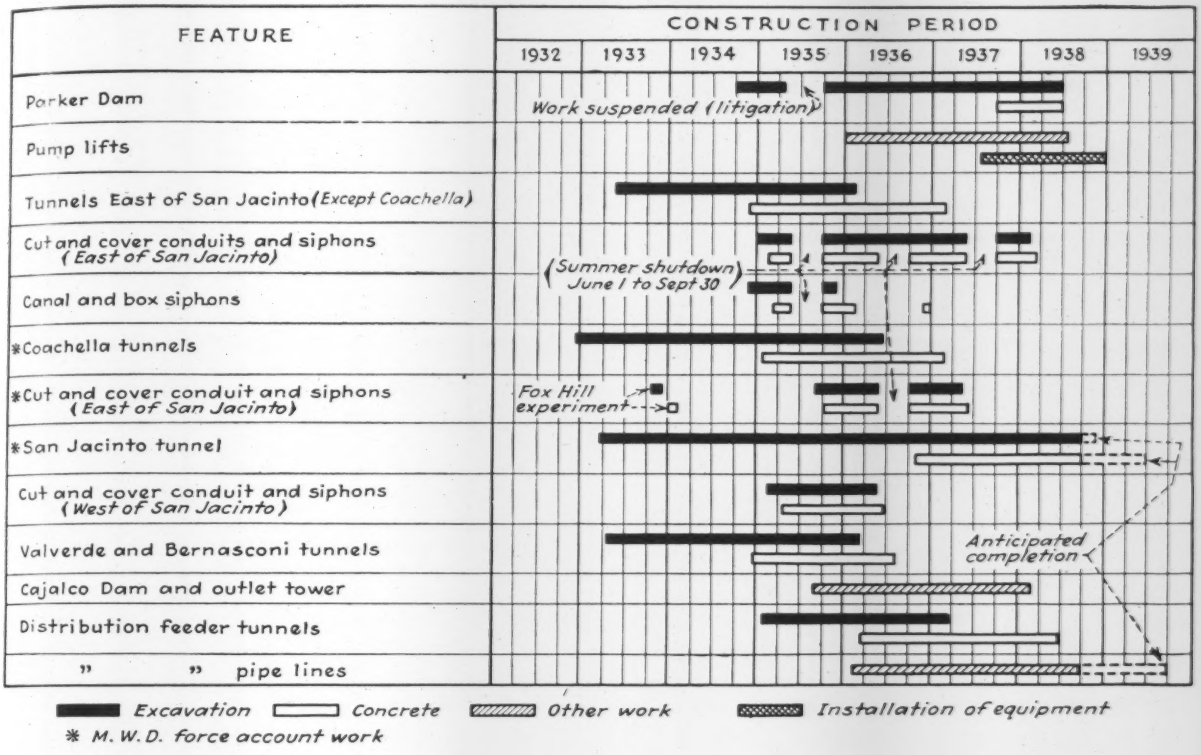
Care and safety of employees

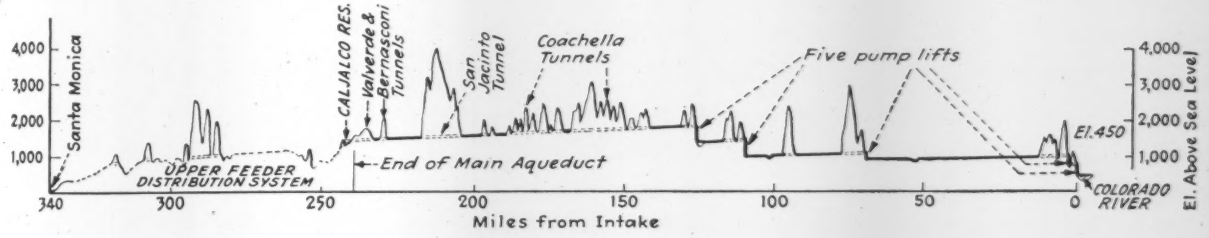
Most of the 35,000 persons employed on the Colorado River aqueduct have resided in one or more of the 35 construction camps which were provided by the district and its contractors. During the period of residency they depended upon district facilities for water and light; the district also provided excellent food, medical care and a furnished room, usually air cooled, and with regular changes of bed linen. The hazards incident to heavy construction were minimized and individuals on the job were safeguarded by the district's safety organization and regulations. Injured workmen were cared for in specially built, well equipped hospitals near at hand. Time lost on account of injuries was compensated for in full. Workmen were charged $1.45 per day for board, room and medical attention. Actually this charge did not cover the total cost of the services provided, but losses which may have accrued are believed to have been more than offset by returns in extra effort and loyalty.

At the beginning of construction a firm policy on safety was translated into results by a safety organization. This consisted of a safety engineer and four assistants, whose duty it was to actively promote safety and to inspect regularly and report upon all places of work. The constant enforcement of the safety rules and regulations was the responsibility of the engineers and inspectors on the various jobs.

The accident frequency rate steadily declined as the work went forward. At the end of 1937 the average tunnel rate expressed as the number of lost-time accidents per million man-hours worked was 144 compared with 151 which is the average rate for previously built California tunnels. The average frequency rate for surface construction for the same period is 70.

CONSTRUCTION SCHEDULES ON MAJOR AQUEDUCT FEATURES





TYPICAL UNIT COSTS, AVERAGED, FOR PRINCIPAL FEATURES OF MAIN AQUEDUCT

Item	Size ft.-in.	Total length in. ft.	Excavation and Support: Cu. yd. per lin. ft.	Excavation and Support: Percent supported	Excavation and Support: Cost per lin. ft. (Dollars)	Concreting: Yardage per lin. ft.	Concreting: Cost per lin. ft. (Dollars)	Backfilling: Cu. yd. per lin. ft.	Backfilling: Cost per lin. ft. (Dollars)	Access* Cost per lin. ft. (Dollars)	Totals Cost per lin. ft. (Dollars)
TUNNELS											
Whipple Mountain }	16 0	32,238	10.99	18.7	63.71	2.82	25.34	.....	....	6.92	95.97
Corcomb ..... { Typical con-	16 0	17,795	11.31	50.3	83.15	2.84	37.85	.....	....	3.39	124.39
Whitewater ..... { tract tun-	16 0	10,232	11.49	100.0	101.26	2.33	19.62	.....	....	4.50	125.38
Valverde (wet) ... { nels	15 3	38,015	11.09	60.4	87.21	2.90	31.03	.....	....	3.77	122.01
All contract tunnels	.....	239,255	11.51	57.0	85.15	2.88	30.83	.....	....	4.43	120.41
Coachella tunnels (Force account)	16 0	178,142	11.74	68.0	65.84	4.23	30.15	.....	....	2.21	99.20
All tunnels except San Jacinto	.....	417,397	.....	....	77.11	....	30.76	.....	....	3.48	111.35
CONDUIT, CUT & COVER											
Thirteen contract schedules	16 0	272,190	41.63	....	12.73	4.21	34.31	21.70	2.30	....	49.34
Two force account schedules	16 0	12,331	37.05	....	6.49	3.59	41.72	17.57	2.16	....	45.37
All conduit	.....	284,521	41.47	....	12.51	4.18	34.63	21.53	2.29	....	49.43
SIPHONS											
Three contract schedules	16 0	2,385	29.24	....	19.70	3.49	93.72	12.70	2.60	....	116.02
Thirteen contract schedules	12 4	86,731	16.60	....	6.79	1.98	44.12	9.10	1.01	....	51.92
One force account schedule	12 4	9,738	22.11	....	9.17	2.10	78.11	18.62	2.90	....	90.18
All 12 ft. 4 in. siphons	12 4	96,469	17.15	....	7.03	1.99	47.55	10.05	1.20	....	55.78
Eight contract schedules, square barrel siphons	9 9	29,150	25.49	....	6.91	3.50	76.45	13.84**	6.12**	....	89.48
LINED CANAL											
Nine contract schedules											
Top width:	55.13 ft.	327,475	23.45	....	5.17	1.42	18.46	.007**	.14**	....	28.77

* Approach cut, adits and shafts. ** Includes riprap; assumed 1 sq. yd. of riprap equivalent to 1 cu. yd. backfill.

Unit costs include payments to contractors, materials supplied by the district and engineering supervision.

PRINCIPAL CONSTRUCTION CONTRACTS AND PERSONNEL OF CONTRACTORS' ORGANIZATIONS ON THE COLORADO RIVER AQUEDUCT

CONSTRUCTION FEATURE	DATE CONTRACT AWARDED	CONTRACTOR	HOME OFFICE	CONSTRUCTION SUPERINTENDENTS	DATE WORK COMPLETED	COMPLETED COST OF CONTRACT WORK*
MAIN AQUEDUCT TUNNELS						
Colorado River, Copper Basin 1 and 2, Whipple Mountain	June 16, 1933	Walsh Construction Co.	Davenport, Iowa	Floyd Huntington & J. H. Gill	Jan. 26, 1937	$5,062,999
Iron Mountain — East Portion	April 21, 1933	Winston Brothers Co.	Minneapolis, Minn.	E. A. Barnard, Excav.–R. V. Johnson, Conc.	Oct. 30, 1936	3,186,425
Iron Mountain — West Portion	April 21, 1933	The Utah Construction Co.	San Francisco and Ogden	Ben Arp	Oct. 23, 1936	2,293,668
Coxcomb	April 21, 1933	Winston Brothers Co.	Minneapolis, Minn.	E. A. Barnard, Excav.–R. V. Johnson, Conc.	April 26, 1937	2,213,554
East Eagle Mountain	Feb. 2, 1934	Broderick and Gordon	Denver, Colo.	C. V. Kavanaugh — Excav.	July 23, 1937	1,050,261
West Eagle Mountain — East Portion	June 2, 1933	Broderick and Gordon	Denver, Colo.	John Wills — Conc.	May 18, 1937	1,954,612
West Eagle Mountain — West Portion	June 2, 1933	L. E. Dixon and Bent Bros., Inc.	Los Angeles, Calif.	Paul Guinn	Mar. 12, 1936	1,347,563
Hayfield No. 1	June 2, 1933	The Hunkin Conkey Constr. Co.	Cleveland, Ohio	Geo. B. Hoag	Jan. 9, 1936	1,176,380
Hayfield No. 2	June 2, 1933	Shofner and Gordon	Los Angeles, Calif.	H. E. Warden	July 27, 1935	654,295
Cottonwood	April 21, 1933	J. F. Shea Co., Inc.	Los Angeles, Calif.	Gilbert J. Shea	Dec. 29, 1935	2,736,891
Mecca Pass Nos. 1, 2, and 3	June 2, 1933	Morrison-Knudsen Co.	Boise, Idaho	S. A. Dahlberg, Excav.— Geo. Fortier, Conc.	Feb. 10, 1935	797,969
Whitewater Nos. 1 and 2	June 16, 1933	West Construction Co.	Boston, Mass.	H. E. Carleton	April 15, 1935	1,282,925
San Jacinto	Feb. 10, 1933	Wenzel and Henoch — (By M. W. D. on force account since Feb. 12, 1935)	Milwaukee, Wis.	Otto Seefeld	.....	†1,754,515
Bernasconi	April 7, 1933	Hamilton & Gleason Co.	Denver, Colo.	H. J. King, Excav.— H. S. Stoker, Conc.	Nov. 21, 1935	693,174
Valverde	April 7, 1933	The Dravo Contracting Co.	Pittsburgh, Penn.	R. W. Remp	Oct. 18, 1936	4,504,507
MAIN AQUEDUCT SURFACE WORK						
Canal; conduit; siphon	Oct. 19, 1934	Aqueduct Construction Co.	San Francisco and Los Angeles	S. T. Corfield	June 24, 1937	5,3344 50
Canal; conduit; siphon	Oct. 19, 1934	Barrett & Hilp and Macco Corp.	San Francisco and Los Angeles	H. W. McKinley & B. H. Evans	May 25, 1937	4,581,178
Canal	Oct. 19, 1934	Jahn & Bressi Constr. Co.	Los Angeles, Calif.	Vincent Bressi	Mar. 18, 1937	1,337,250
Canal	Oct. 19, 1934	Jahn & Bressi Constr. Co.	Los Angeles, Calif.	Vincent Bressi	Nov. 24, 1936	1,420,469
Canal; siphon	Oct. 19, 1934	C. W. Wood and M. J. Bevanda	Stockton, Calif.	Clyde W. Wood	July 28, 1937	2,300,693
Canal; conduit	Oct. 19, 1934	The Utah Construction Co.	San Francisco and Ogden	Ben Arp	May 15, 1937	1,563,325
Conduit; siphon	Oct. 19, 1934	Three Companies, Inc.	Denver and Albuquerque	C. G. Clapp & C. V. Kavanaugh	Nov. 6, 1937	1,965,468
Conduit; siphon	Oct. 19, 1934	Thompson-Starrett Co., Inc.	New York, N. Y.	Rodney J. Smith	.....	‡4,332,000
Little Morongo Siphon	Nov. 17, 1933	United Concrete Pipe Corp.	Los Angeles, Calif.	Fred Jenkins	Aug. 20, 1934	82,621
Conduit; siphon	Nov. 9, 1934	J. F. Shea Co., Inc.	Los Angeles, Calif.	W. F. Rennebohm	.....	‡4,225,000
Siphon	Jan. 11, 1935	Morrison-Knudsen Co.	Boise, Idaho	J. O. Young	Sept. 16, 1936	560,821
Conduit; siphon	Dec. 7, 1934	Griffith Company	Los Angeles, Calif.	Harry Davis	Oct. 13, 1936	2,739,600
MAIN AQUEDUCT APPURTENANT WORKS						
Parker Dam — constructed under co-operative agreement	Feb. 10, 1933 Aug. 23, 1934	U. S. Bureau of Reclamation Six Companies, Inc.	Denver, Colo. San Francisco, Calif.	E. A. Moritz & F. T. Crowe	.....	‡8,716,000
Intake and Gene pump. plant bldgs. and appurt. works	Nov. 29, 1935	Winston Bros. Co. and William C. Crowell	Minneapolis and Pasadena	R. A. Crowell	.....	‡2,572,000
Iron Mountain pump plant bldgs.	Jan. 24, 1936	Wood and Bevanda	Stockton, Calif.	Clyde W. Wood	Sept. 1, 1937	1,072,149
Eagle Mountain pump plant bldgs.	Mar. 27, 1936	L. E. Dixon Co.	Los Angeles, Calif.	F. H. Strohecker & J. H. Larkin	.....	‡1,291,000
Hayfield pump plant bldgs.	Sept. 4, 1936	L. E. Dixon Co. & Case Const. Co., Inc.	Los Angeles & Alhambra	Crawford, Strohecker & W. N. Evans	.....	‡1,883,000
Gene Wash and Copper Basin dams	Mar. 26, 1937	J. F. Shea Co., Inc.	Los Angeles, Calif.	F. T. Crowe	.....	‡1,300,000
230-kv.— Boulder Dam trans. line	Sept. 27, 1935	Fritz Ziebarth	Long Beach, Calif.		Aug. 1937	1,907,622
Whipple Patrol rd. trans. line	Feb. 25, 1935	Bennett and Taylor	Los Angeles, Calif.		Nov. 1935	92,699
Boulder Telephone Line	Sept. 13, 1935	Newberry Electric Corp.	Los Angeles, Calif.		May 1936	85,889
Fence schedule No. 1	Nov. 19, 1937	Anchor Post Fence Co.	Los Angeles, Calif.	J. R. Coston	.....	‡525,000
Fence schedule No. 2	Nov. 19, 1937	Pittsburgh Steel Co.	Pittsburgh, Penn.	H. W. M. Coleman	.....	
Fence schedules 3, 4 and 5	Nov. 19, 1937	Los Angeles Fencing Co.	Los Angeles, Calif.	H. Henderson	.....	
DISTRIBUTION TUNNELS						
Monrovia Nos. 1, 2, and 3	Dec. 21, 1934	West Construction Co.	Boston, Mass.	H. E. Carleton	.....	‡3,200,000
Monrovia No. 4; San Rafael 1 and 2	July 26, 1935	L. E. Dixon Co., Bent Bros., Inc. and Johnson, Inc.	Los Angeles, Calif.	L. E. Dixon	.....	‡1,520,000
Sierra Madre	Aug. 9, 1935	J. F. Shea Co., Inc.	Los Angeles, Calif.	Ed. H. Shea	Oct. 31, 1936	459,665
Pasadena	Dec. 21, 1934	L. E. Dixon Co., Bent Bros., Inc. and Johnson, Inc.	Los Angeles, Calif.	H. J. King	April 29, 1937	1,044,083
Pasadena extension	Aug. 9, 1935	L. E. Dixon Co., Bent Bros., Inc. and Johnson, Inc.	Los Angeles, Calif.	H. J. King	Nov. 24, 1936	411,445
DISTRIBUTION PIPE LINES AND APPURTENANT WORKS						
Cajalco Reservoir	Aug. 16, 1935	Griffith Company	Los Angeles, Calif.	Franz Fohl	Feb. 9, 1938	5,452,053
Distribution headworks structure	Mar. 25, 1938	The Contracting Engineers Co.	Los Angeles, Calif.	Julian Huddelston		‡295,000
Precast concrete pipe	Jan. 10, 1936	Amer. Conc. and Steel Pipe Co.	Los Angeles, Calif.	D. H. Rankin	Dec. 23, 1937	1,864,625
Steel pipe and steel bridge	Jan. 10, 1936	Western Pipe & Steel Co.	Los Angeles, Calif.	L. L. White	Nov. 24, 1937	4,726,321
Precast concrete pipe	Nov. 1, 1935	Amer. Conc. and Steel Pipe Co.	Los Angeles, Calif.	J. C. Connell	June 18, 1937	2,443,103
Precast concrete pipe	Dec. 20, 1935	J. F. Shea Co., Inc.	Los Angeles, Calif.	Ed. H. Shea		‡3,350,000
Precast concrete pipe	Nov. 1, 1935	United Concrete Pipe Corp.	Los Angeles, Calif.	Charles Johnston	Mar. 20, 1937	1,487,646
Canyon crossings	Feb. 19, 1937	Basich Bros.	Torrance, Calif.	Dick Noble	.....	‡365,000
Precast concrete pipe	Aug. 7, 1936	United Concrete Pipe Corp.	Los Angeles, Calif.	Roy Richards	.....	‡1,400,000
Mortar-lined steel pipe	Sept. 10, 1937	J. F. Shea Co., Inc.	Los Angeles, Calif.	H. F. Rennebohm & Charles H. Shea, Jr.	.....	‡3,125,000

* Includes District-furnished materials, engineering and administration.
† Construction being completed by District forces.
‡ Estimated.

Driving An Extremely Difficult Tunnel

B. C. LEADBETTER

General Superintendent, San Jacinto Tunnel, Metropolitan Water District of Southern California

Wet, faulty formations in the San Jacinto yielded 40,000 g.p.m. at times; its problems taxed ingenuity to the utmost and controlled the aqueduct completion date

THE 13½ MILE SAN JACINTO tunnel presented a curious combination of difficulties; inflows ranging up to 15,800 g.p.m. in or near a single working face continued with discouraging persistence; water pressures as high as 600 lb. per sq. in. caved in headings or brought down the arch; water had to be pumped out against an 800-ft. head through a shaft that was flooded repeatedly while the work was under contract; new methods of advance grouting had to be developed, and repeated relocation of portions of the tunnel were necessary. Altogether the driving of "old San Jack" was the most difficult item in constructing the aqueduct. However, in the end all the obstacles were overcome and the job is nearing completion as this is being written. The following is a summary of the problems met and the methods used in their solution.

San Jacinto tunnel begins where the westward-bound Colorado River aqueduct enters the north slope of Mount San Jacinto in San Gorgonia pass, near Banning, Calif. From El. 1,535 at this portal the tunnel slopes downward to the west on a grade of 3.43 ft. per mi. This location and grade were selected after careful planning, core drill exploration and a study of earthquake faults and other geological hazards. With as much data as were to be had on formations, a location was chosen permitting access at the east and the west portals and at two shafts; Cabazon shaft near the east end (261 ft. in depth and 935 ft. off the tunnel line) and Potrero shaft, 861 ft. in depth, located on the line. The 8.4-mi. length of tunnel between these two shafts determined not only the time required for driving the tunnel itself, but was also the controlling factor in completion of the entire project.

Delay at the very outset in 1932 occurred when, after bids had been received, the low bidder failed to qualify; the contract was finally awarded on March 17, 1933, to the second lowest bidder, the Wenzel and Henoch Construction Co. of Milwaukee, Wis., for $7,339,100.

Initial plan of attack

In providing access to the main bore, the contractor elected to attack through circular, concrete-lined shafts 15 ft. in diameter at the Cabazon and Potrero locations. Some four months later operations were begun at the west portal entering through a short slope to grade. Due to its short distance from Cabazon, the east portal access was not opened immediately.

No difficulty was encountered in sinking the Cabazon shaft through the firm, undisturbed granodiorite; a minor fault crossing the adit connecting shaft and tunnel, produced water at the rate of 1,400 g.p.m. and somewhat slowed down excavation. On Feb. 19, 1934, operations on the main tunnel were started in each direction from the bottom of Cabazon shaft.

In sinking Potrero shaft, water was encountered on a shear zone at a depth of 130 ft. Inflows of 30 to 500 g.p.m. persisted to the bottom. Tunnel grade, reached in April, 1934, was in good granite and the operating station was opened without difficulty. In July 1934, the heading being driven eastward encountered

Fig. 1. Who said this tunnel was wet?

the same fault crossed by the shaft. A sudden inrush of water at 7,500 g.p.m., accompanied by 1,000 cu. yd. of detritus, quickly flooded the tunnel and rose to a depth of 647 ft. in the shaft.

Seven weeks later, by which time the water depth had been reduced to 50 ft., the 12-in. discharge pipe supporting one of the three sinking pumps parted in the shaft, dropped the pump and damaged one of the others so that the shaft was again flooded, this time to a depth of 540 ft. Unwatering was accomplished in November 1934. When further advance was made in the east heading more water was encountered, in addition to the 3,500 g.p.m. already coming in, and the shaft was flooded for the third time; final dewatering was not accomplished until December 1934. Meanwhile, operations through fractured, wet rock by the west portal were carried on heading-and-bench methods; steel ribs and plate liners were used for supports.

On Feb. 12, 1935, it was decided that satisfactory progress was not being made and that work was being unnecessarily delayed, the district therefore exercised its right under the contract and took over full charge of operations to complete the tunnel.

On March 13, 1936, although the tunnel had been holed through between Potrero and west portal, and on the opposite end had been advanced 6,280 ft. east of Cabazon, a total of only 10,812 ft. had been excavated on the critical tangent between Cabazon and Potrero. Of this advance 2,017 ft. was east of Potrero and 8,795 ft. was west of Cabazon; 32,699 ft. remained to be driven. Surface geology indicated several major faults ahead which might be more difficult to penetrate than those so far experienced.

Construction on other portions of the aqueduct was fully up to schedule, hence to avoid costly delay in completing the project as a whole it was imperative that steps be taken to expedite construction. The possibility of building another access shaft had been studied repeatedly, but had not been adopted because of the time required for such construction and the

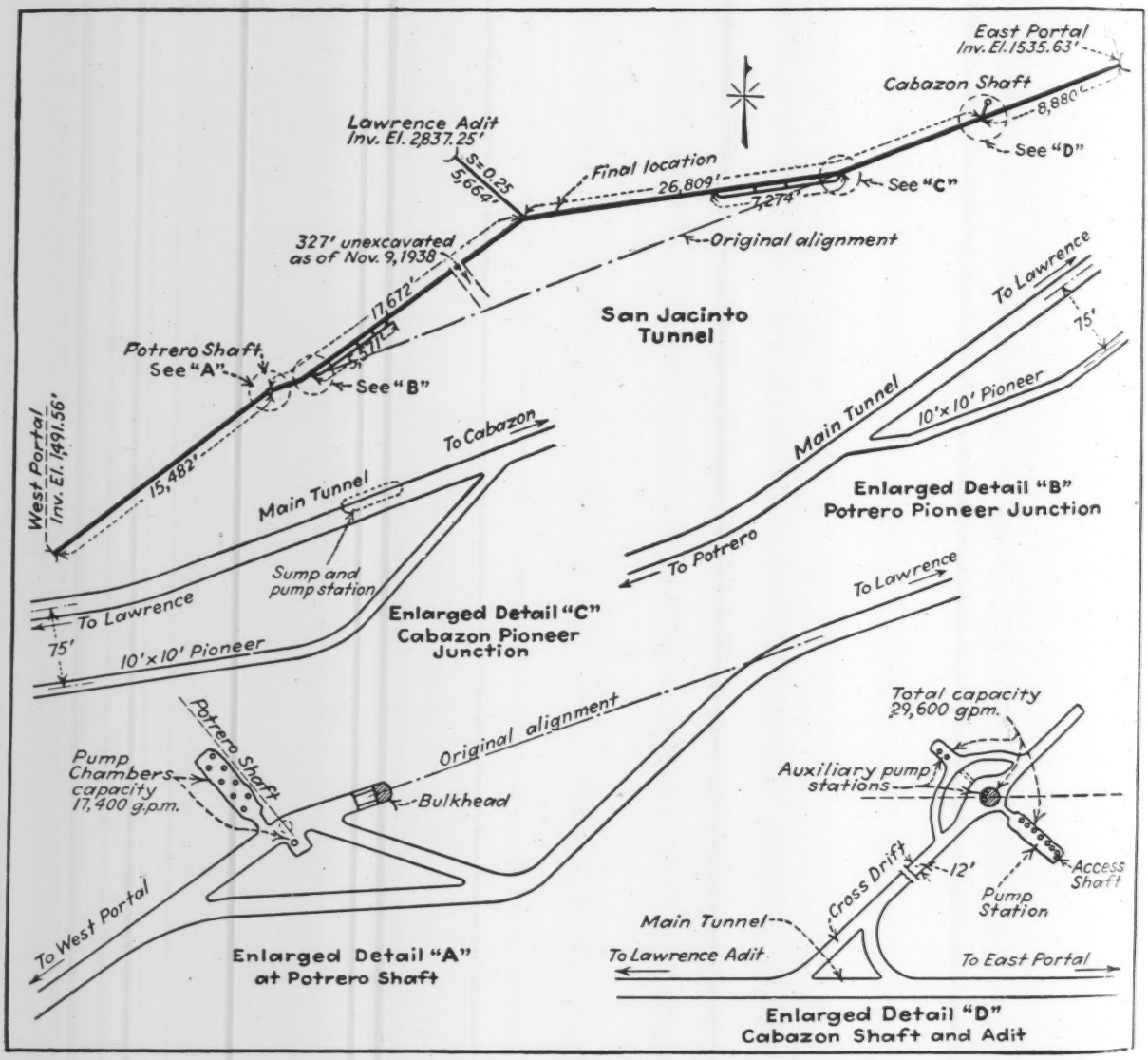


Fig. 2. Difficulties encountered in driving San Jacinto tunnel are reflected in the changes, detours and realignment here shown.

additional cost it would involve. The conditions obtaining early in 1936, however, demanded heroic measures and on March 23 ground was broken on an incline 5,664 ft. long, known as Lawrence adit, situated about midway between Cabazon and Potrero shafts. Decision to build this adit was based on the belief that its use would compensate for initial construction delays and shorten the main tunnel driving by about 12 months.

There was opportunity for a reasonably economical entry to the tunnel at the Lawrence location because (1) here an adit could take advantage of a deep ravine, 9,000 ft. north of and nearly parallel to the original tunnel line and (2) at this stage of construction it was still possible to relocate the unexcavated portion of the Cabazon-Potrero section of the tunnel so as to throw it toward the new adit. The problem involved; (1) intensive study of the surface geology, particularly the fault systems of the region; (2) a determination of the most practical slope on which to drive the adit, and (3) the balancing of costs controlled by the relative lengths of adit and tunnels on various locations.

The adit was located on the south side of Lawrence gulch, in what appeared to be relatively undisturbed granite between the McInes fault and another parallel to it on the east. The adit parallels the major fault system and the relocation in the central portion of the tunnel avoided several minor faults likely to be intersected at a very slight angle on the original alignment. Moreover, the major faults common to both locations would be crossed at a more favorable angle by the relocated line.

Sinking the inclined adit

The adit portal is 1,324 ft. above tunnel grade, its length on a 25-per cent slope is 5,452 ft. and at the foot of the slope a 212-ft. level section affords space for loading and for a pump station. The increased length of the main tunnel, caused by swinging the location to the north to meet the adit, is 1,022 ft.; the intersection point is about 4,000 ft. north of the original location. In the first 1,400 ft. of the adit the cross-section was made 10x10 ft. From this point on it was made 11x12 ft. to give more clearance for driving operations.

Sinking operations in an adit inclined at 25 deg. called for experiments in mucking the broken material. A start was made with a dragline operated from a long boom dragging onto a belt conveyor. An innovation involving a heavy belt conveyor, provided with a removable cover for receiving muck broken out by blasting, was then tried and abandoned. The mucking equipment finally employed was a 60-hp. Conway, altered so that the conveyor belt was parallel to the tracks and the dipper could load muck directly on the belt. To compensate for lack of traction on the slope a balance was provided by a heavy car offset on a narrow track, attached to a cable, acting as a counter-weight.

During sinking operations dewatering was handled by small electrically operated air pumps delivering to booster stations in the shaft. On completion of the incline, pumping stations at halfway points and at the bottom were equipped to handle a total of 14,000 g.p.m. through two 18-in. high-pressure discharge pipes. The power installation provided for a total capacity of 12,000 kva.

The hoisting installation included a 600-hp. single drum, double brake hoist, operating a 16½-ton skip hauled by a 1¼-in. cable. A sinking hoist driven by two 400-hp. motors, was kept in reserve as a standby.

Concurrently with the sinking of Lawrence adit, studies inflenced a decision to drive pioneer tunnels parallel to the main bore, 10x10 ft. in diameter, offset 75 ft. from the center line. It was believed that a pioneer tunnel could be driven at greater speed and thus would (1) give advance information as to the location and extent of bad ground, (2) improve drainage, (3) afford an additional entry, and (4) provide a possible means of detouring utilities and traffic in sections where excavation had been delayed. Such pioneers were started at Cabazon and Potrero in 1936.

Pioneer tunnels, however, did not always give advance indication of the true nature of the rock, neither did they always accomplish drainage in the main tunnel due to the broken formation and consequent sudden changes in the rock.

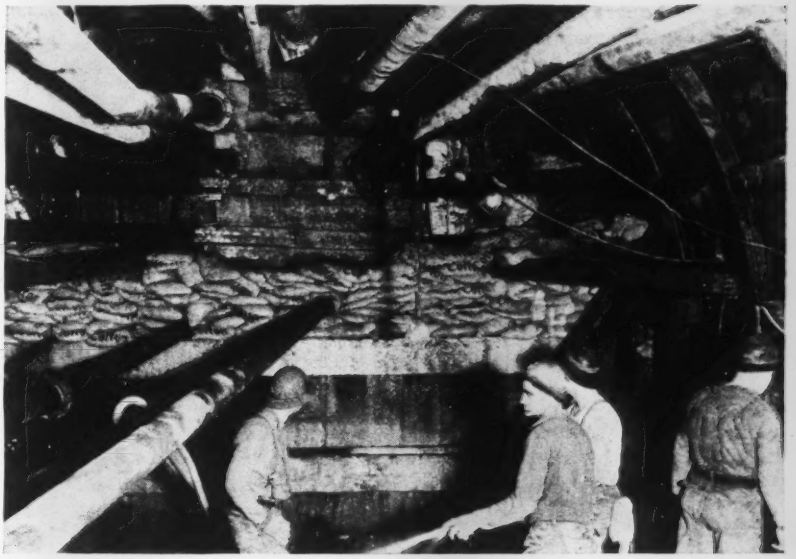


Fig. 3. San Jacinto tunnel sometimes required full face bulkheads for high-pressure grouting ahead of the drilling operations.

Pumping equipment

Immediately after taking over the tunnel from the contractor, steps were taken to provide adequate pumping. This required additional electric power facilities and installation of a 30-in. discharge from heading to a central pump station. Such stations, put in at the bottoms of Cabazon and Potrero shafts, were built in bottle-shaped chambers cut into the rock at right angles to the shaft. Here, behind steel bulkheads, pump installations of 16,000 g.p.m. were arranged for remote control. These stations had water tight construction and forced ventilation, cooling and lubrication.

Cabazon station was made accessible by a small auxiliary shaft from the surface, used also by power, ventilation and control lines. At Potrero, because of the depth, no separate access shaft was provided; remote control lines passed through the main shaft.

During 1936, Cabazon shaft pumping volume was increased by 12,500 g.p.m., making a total installed capacity of 28,500 g.p.m. To permit the delivery of a maximum capacity in tunnel pipe lines, a "booster station" of 27,000 g.p.m. was set up 8,800 ft. west of the adit from the bottom of Cabazon shaft. For a short time in 1937 this booster operated at full capacity.

With the holing though of Potrero-West Portal leg, and the completion of the Cabazon-East Portal section, water was discharged at the portals and the pump lift in the shafts was eliminated. Potrero pump station was dismantled and the equipment transferred to Lawrence adit. The Cabazon station was held intact to provide a standby in case the pumps delivering upgrade to the east portal should be overtaxed.

With advance of the headings, difficulty arose through inflows of water under high pressure and heavy ground conditions in faulted and fractured zones. It was necessary to devise and use new methods of attack as well as means for protecting completed sections.

Some unusual expedients

Finding that the Potrero-east heading had encountered a difficult fault condition with caving ground and water under high pressure, a crossing of the fault was effected by a detour 150 ft. to the south. New water flows in large volumes persisted in all sections. At 1,900 ft. east of Potrero shaft, a surge of larger volume than had previously been encountered resulted, at one time, in 9,000 g.p.m. entering the tunnel in a section 135 ft. long. Test holes drilled in the face at Cabazon encountered water pressure exceeding 600 lb. per sq. in. Such experiences, varying only in degree, were not uncommon; the usual treatment was to case the holes and control the flow with valves.

In 1937 a fissure was cut in a pioneer tunnel releasing a flow of 6,000 g.p.m. That same year the Goetz fault at Potrero brought in water of 4,000 to 5,000 g.p.m. through feeler holes. At one time a discharge of 15,800 g.p.m. occurred in or near the working face for a short time. The peak discharge for the entire tunnel, reached in February 1938, totaled 40,000 g.p.m. Heavy surges of water brought in quantities of fault filling and debris. The attack in such zones required careful and safe methods.

Under favorable conditions inflows were controlled by pumping sand and grout into seams and fractures. Test holes 35 ft. deep were drilled regularly into the working face and, where water-bearing fissures were encountered, grout was forced into these holes under pressure of 1,600 lb. per sq. in. Where the rock was so fractured that there was much leakage through the face and a considerable amount of grout wasted into the tunnel, bulkheads were built of sand bags cemented together and braced by heavy timbers through which drainage and grout pipes were operated. (*ENR* May 7, 1936, p. 661.)

Shutting off water

Sealing off water behind the face was accomplished where necessary by heavy gunite rings, applied behind a grill of reinforcing steel, forming a barrier and a template for the cement casing thus built up. Drainage pipes were provided to carry off excess water, through which grout was later pumped to make a final seal and shut off.

Crossing the Goetz fault, the pioneer tunnel was of great advantage because through it a section of the main tunnel 1,300 ft. long was driven during stoppage of work on the main heading. This fault not only yielded heavy flows of water but on one occasion released about 3,000 cu. yd. of sand and detritus into the tunnel.

The Goetz fault was eventually passed by working back from the pioneer cross-cut by top pilot drift, winging out into a wall-plate top heading and later removing the bench. Driving of the top pilot involved the use of steel spiling, breastboards and often the replacement of crushed and disturbed timbers.

After crossing the last known major fault, the pioneer tunnels were discontinued in the summer of 1937. At this time driving conditions in the main heading had improved so much that it was impossible to keep the pioneer much in advance of the main bore.

Equipment and material

Electric power for driving operations delivered at 66,000 volts was stepped down for 2,300- and 440-volt motors by transformer banks whose total capacity was 36,000 kva. The largest power use was for pumping. In May, 1938 a total of 5,000,000 kw.-hr. had been used in handling 1,385,000,000 gal. On the high-lift pumps 700-hp. motors were used. The total capacity of electric motors used in the tunnel for hoisting, hauling, air compressors, mucking machines, etc., was 30,600 hp.

Mechanical equipment for tunneling operations includes double-drum mine hoists lifting combination rock skips and man cages, 5-cu. yd. muck cars, haulage locomotives, air compressors, and automatic rock drills. As many as 11 automatic drills are mounted on a single drill carriage. In firm fresh granite, 72 holes are drilled to a round using air pressure of 100 lb. per sq. in. Blasting is done with 40 per cent gelatin dynamite; from 5 to 7¼ lb. per cu. yd. is required to break the rock in the desired manner.

Mucking, except for the special machines in Lawrence adit, is done with 60- and 75-hp. conveyor-type muckers, loading 5-cu. yd. cars transferred over a portable track on a California-type switch. Muck trains are hauled by 12-ton locomotives; general switching is done by 8-ton locomotives on 40-lb. rails and 6x8-in. ties.

Methods of supporting bad ground has included rib sections of 6-in. I-beam steel, 8-in. steel, close fitted steel liner plates on steel ribs, 12x12-in. timber sets and 16x16-in. timber sets placed at times skin to skin. No special equipment, except drill carriages that mounted only 7 drills, was required in the pioneer tunnels; their 10x10-ft. section was sufficient for the standard mucking and hauling equipment used in the main tunnels.

Placing concrete lining in San Jacinto tunnel to reduce friction and to provide permanent support (which is carried on simultaneously with driving operations) is, in itself, a major operation. The lining was half completed in August, 1938. Some sections have an invert thickness of

30 in. and a minimum of 24 in. elsewhere. Cement grout is forced in behind the lining under high pressure to seal off water seepage and to fill voids. The lining is placed by pumping machines of 1- and 2-cu. yd. capacity delivering the concrete behind portable steel forms. Where necessary this operation is carried on in such a way as to permit traffic through the forms to and from the tunneling operations ahead. Where driving operations are not a hindrance, concrete lining of walls and arch can be completed at the rate of 160 ft. per day.

Excavation in the last mile of the tunnel began July 22, 1938. It is thought that excavation will be completed about Dec. 15, 1938, and that concrete lining will be finished, ready for water to flow from the Colorado River to the Los Angeles area about Aug. 31, 1939.

Large Pumps of Unprecedented Efficiency

J. M. GAYLORD

Chief Electrical Engineer, Metropolitan Water District of Southern California

Improved design for 200 sec.-ft. units developed by research, was used in equipping the five plants that will lift Colorado River water 1,616 ft.

PARTICULAR EMPHASIS was placed on careful design of pumps for lifting Colorado River water the required 1,616 ft. in the aqueduct because of the annual power cost. Even with unusual pump efficiencies the annual pump operating cost of the completed system will be $5,500,000 at the present rates for Boulder power. The district has a right to take 1,100,000 acre-ft. of water annually from the supply stored in Lake Mead and 2,250,000,000 kw.-hr. will be required annually (about 300,000 kw.) to operate the pumps on the aqueduct. At the outset only three of the ultimate nine units are being installed in each plant. These initial units, with housing, connections and some provision for the units to come later, are costing $22,000,000. The additional units will bring the total cost for pumping equipment, installed, up to $33,000,000.

The success of this unprecedented pumping operation will depend largely on excellence of design in the pumps themselves. Hence, in order to insure selection of the most suitable type and to improve existing designs, a 2-yr. program on investigation of centrifugal pump per-

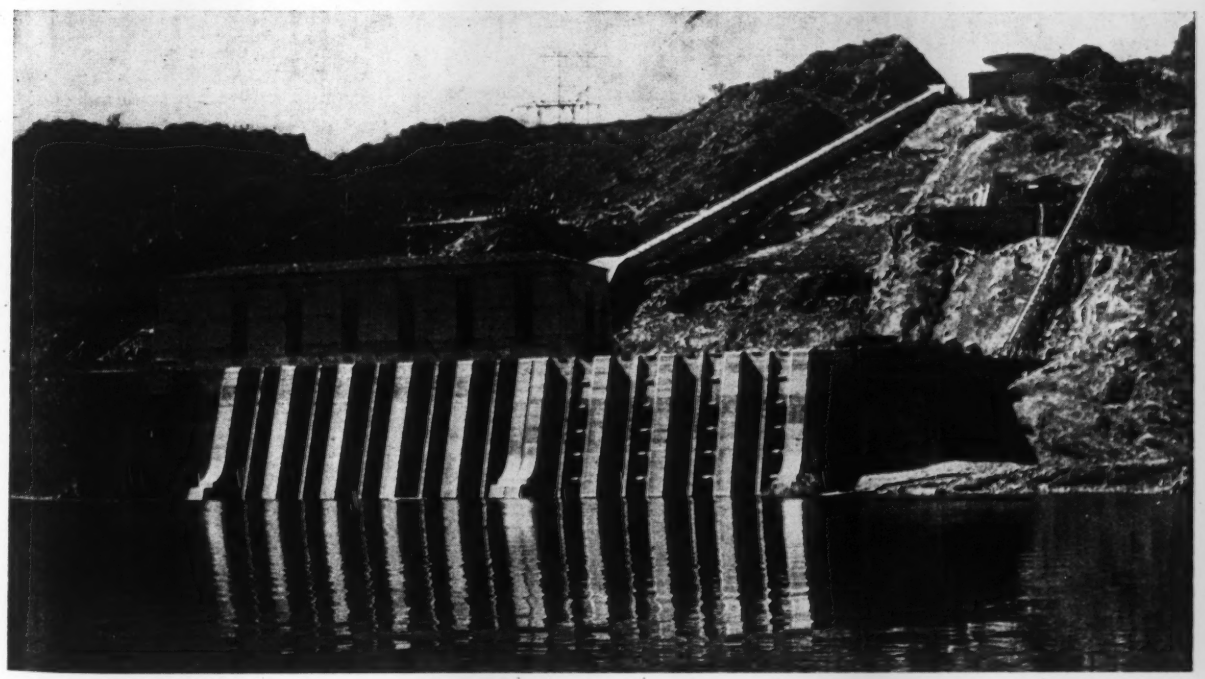


Fig. 1. Intake pumping plant on the Colorado River, before filling the pool behind Parker Dam.

formance was carried out prior to writing specifications for the aqueduct pumps. With the assistance of the technical staff at California Institute of Technology and the cooperation of several prominent pump manufacturers, a pump testing laboratory was built and operated to determine the best operating characteristics of pumps and valves. (*ENR* Jan. 14, 1937, p. 45.) Previous experience in the design of comparable equipment was very limited. Moreover, conflicting recommendations of designers as to speeds, number of stages and inlet conditions indicated the need for thorough study of these phases off design. Designs and estimates were also made to determine the comparative cost of alternative layouts of pumping plants.

These studies led to selecting pumps of 200-sec.-ft. capacity, a size well adapted to first class mechanical work and which, at the same time, makes it possible to increase capacity of the plants in reasonable steps to meet a growing water demand. In the completed plants there will be eight operating units and one spare. The units are unique in that each lift is made in a single stage. There are no single-stage pumps of comparable size operating under heads in excess of about 300 ft. Single-stage pumps for lifts on this project were specified only after model tests proved such a design practicable without material reduction in efficiency. The use of this type of pump will effect economies in plant construction many times the cost of the laboratory investigation.

All pumps are of the single-suction vertical type, direct connected to synchronous motors. This design permits a simple station arrangement with the motor above forebay water level and the pump at any desired elevation below the inlet where it is self priming and has the benefit of inlet pressure as a means of preventing cavitation. The setting designs were based on information about cavitation characteristics obtained from laboratory tests on scale models.

In laboratory studies of flow conditions inside model pump casings, it was found that under certain conditions encountered in starting and stopping, the pump impellers are subjected to side thrusts of sufficient magnitude to cause rubbing contact of seal rings unless the shafts have diameters much larger than ordinarily used. Accordingly, the aqueduct pumps have oversize shafts.

High pumping efficiency is of great importance because a saving of 1 per cent under full load will reduce power cost more than $50,000 annually. In fact, a major objective of the testing program was to increase efficiency. This was attained by determination of uncertain factors affecting design and by stimulating competition between rival manufacturers.

Specifications issued in 1935 required each bidder to submit, for test in the district's laboratory before award of contract, a model of one of the full sized pumps offered. Models of each pump contracted for also were tested after award of contracts with the result that the 8-in. models attained efficiencies from 91.5 to 92.5 per cent. Bonuses amounting to $55,000 for each per cent in excess of 88 will be paid after field test of the first installation of three units in each plant.

The important problem of pressure surges in the pump and delivery pipe at the time of starting and stopping pumps was investigated mathematically and by model tests of pump and valve characteristics under all probable conditions of forward and reverse flow. The control of water hammer is entrusted to an automatic device similar to a waterwheel governor which is operated by oil maintained under air pressure in accumulator tanks adjacent to the valve and control mechanism. If the

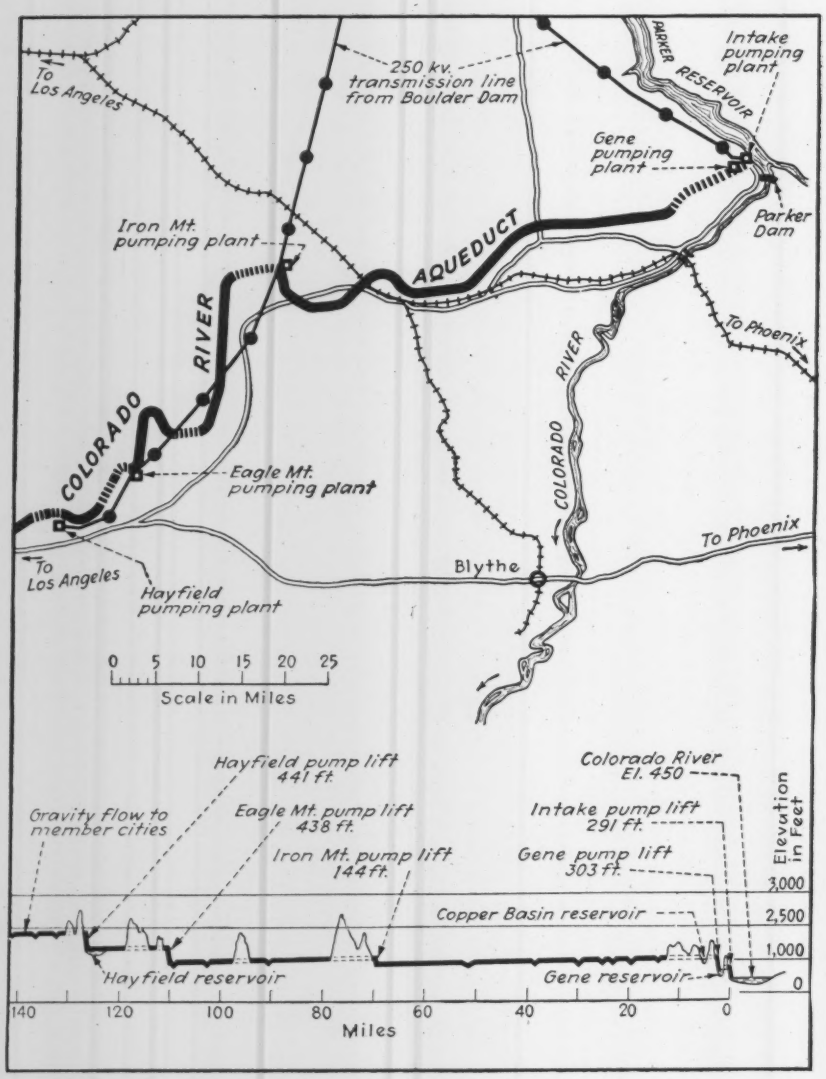


Fig. 2. Plan and profile of the upper end of the aqueduct where the five pumping plants are located.

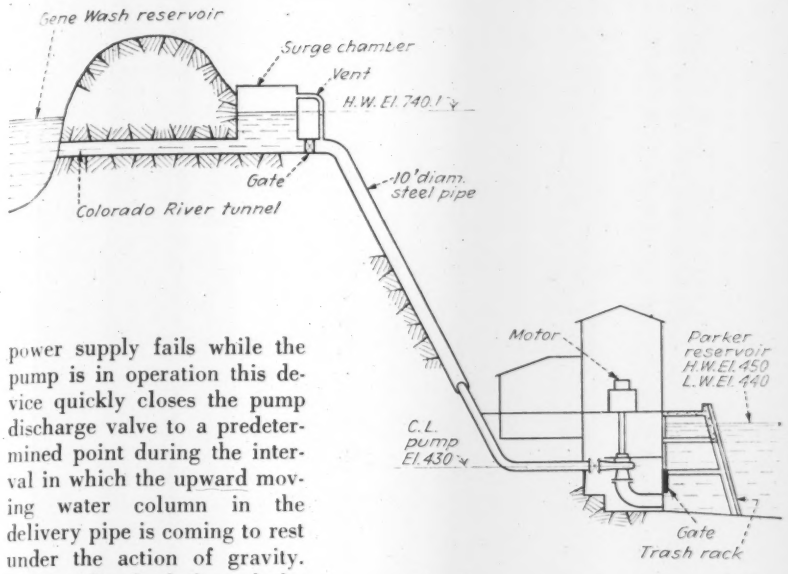


Fig. 3. Schematic profile at the Intake pumping plant.

power supply fails while the pump is in operation this device quickly closes the pump discharge valve to a predetermined point during the interval in which the upward moving water column in the delivery pipe is coming to rest under the action of gravity. Reverse flow back through the pump will then begin but will be gradually checked by slow closure of the discharge valve through the remainder of its stroke. By this means the pressure rise under the most severe conditions probable, in the high-head plants where conditions are the most difficult to control, will be limited to 50 per cent more than normal. The discharge valves are of the rotary plug type, operated by oil pressure cylinders.

A good operating layout

All the pumping plants are similar in design. Each group of three pumps will be connected to one of the three discharge pipes ultimately to be built at each plant. The Intake pumping plant takes water directly from Parker reservoir and raises it 291 ft. to Gene Wash reservoir. Another lift of 303 ft. is made at Gene pumping plant which discharges via Copper Basin tunnels into Copper Basin reservoir. Parker reservoir with a capacity of 717,000 acre-ft. is an excellent settling basin and hence it is expected that water diverted into the aqueduct will have a low silt content. Further removal of silt will occur as the result of retention in Gene Wash and Copper Basin reservoirs, capacities 6,600 to 20,700 acre-ft., respectively, so that outflow from the latter will be practically clear water.

Table I gives statistics for all five plants. Contracts for initial pumping units in all of these were awarded Feb. 8, 1936.

Iron Mountain, Eagle Mountain and Hayfield plants are provided with forebay reservoirs to regulate inequalities in flow and save water in transit when pump operation is interrupted without advance notice, as in the case of power failure. At Iron Mountain and Eagle Mountain, due to lack of natural sites, the reservoirs are limited to a capacity of 100 acre-ft. each; at Hayfield a capacity of 86,500 acre-ft. was developed.

At the Intake plant water enters the pumps through trach racks; at other plants steel intake manifolds distribute the flow to each pump. Iron Mountain, Eagle Mountain and Hayfield plants have some of the pumps equipped with selector valves so that water may be drawn either from the aqeuduct or from the reservoir, as required. Each pump is provided with an intake valve of the butterfly type and a plug valve on the discharge side, so that any pump can be isolated for inspection or repair without

TABLE I — COMPARATIVE FIGURES FOR THE FIVE PUMPING PLANTS

Name of plant	Distance from Intake (mi.)	Average pumping head (ft.)	Runner speed (r.p.m.)	Specific speed	Pump discharge diameter (in.)	Impeller diameter (in.)	Pump manufacturer
Intake	0	294	400	1,700	42	76	Byron Jackson
Gene	3	310	400	1,650	42	78	Byron Jackson
Iron Mountain	70	146	300	2,180	48	74	Allis-Chalmers
Eagle Mountain	110	440	450	1,430	40.5	79.5	Worthington
Hayfield	126	444	450	1,420	40.5	80	Worthington

Fig. 4. The 10-ft. discharge pipe from Gene pumping plant. Supports on each bent are of the ball-and-socket rocker type.

Fig. 5. A bronze pump impeller from which an efficiency of more than 92 per cent is expected.

interfering with the operation of adjacent units.

Power for pumping

Each pump is driven by a vertical, three-phase, 60-cycle, 6,900-volt synchronous motor, water cooled and totally enclosed for recirculation of air. All motors are started at full voltage as induction motors with water in the pump casings and are synchronized automatically by application of field current under control of a relay. The pumps and all major equipment are controlled from a central control room where indicators and instruments inform the operator of conditions throughout the plant. Recording meters will register the flow of water through the pumps.

For the initial installation of three pump units, inlet manifolds, building substructures, pipe line excavation and certain other features of the plants have been completed for the ultimate nine units; superstructures are completed for five.

Power will be supplied from Boulder Dam initially over a single circuit 230-kv. transmission line 237 mi. long, carried on steel towers. The conductors are 795,000 circular mill steel reinforced aluminum cable, except for 10 mi. across Danby dry lake, where 500,000 cir.-mil. hollow copper conductor is used as an additional safeguard against corrosion arising from severe alkali dust conditions. A second circuit from Boulder to Eagle mountain will be needed when the fifth pump is installed in each plant.

Fig. 6. The pumping stations closely resemble power stations. This is the Iron Mountain station.

The entire pumping system has been designed for long life, low maintenance and high efficiency, but many refinements of electrical design usual in modern transmission lines and plants of large commercial power systems to prevent momentary outages have been omitted because on the aqueduct continuity of pumping is not a prime essential. Delivery of water is safeguarded by large terminal reservoirs to such an extent that power interruptions of several days' duration will not materially interfere with the proper functioning of the project as a whole. By this means the cost of the pumping system has been considerably reduced without sacrificing economy in maintenance expense.

Federal authorities have allotted to the district for aqueduct pumping, 36 per cent of the firm energy and all secondary energy that can be developed at Boulder Dam. The firm allotment, amounting to 1,523,000,000 kw.-hr. in 1938 and subject to some diminution annually thereafter, is sufficient to pump about 740,000 acre-ft. per year, or two-thirds of the designed capacity of the aqueduct. When this requirement is exceeded the deficiency can be supplied by the use of secondary Boulder power if available or by purchase of additional firm energy from other allottees. The district also owns one-half of a 100,000-kw. power site at Parker Dam which is to be developed when needed to supplement the power obtained from Boulder for pumping.

The present cost of falling water for the generation of firm energy at Boulder Dam is 1.63 mills per kw.-hr. and for secondary energy 0.50 mills per kw.-hr. The cost of generation and standby service will raise the average cost of electrical energy delivered to the district at Boulder to about 2.6 mills per kw.-hr. The district's requirement for pumping one acre-ft. of water through the five lifts is 2,040 kw.-hr.

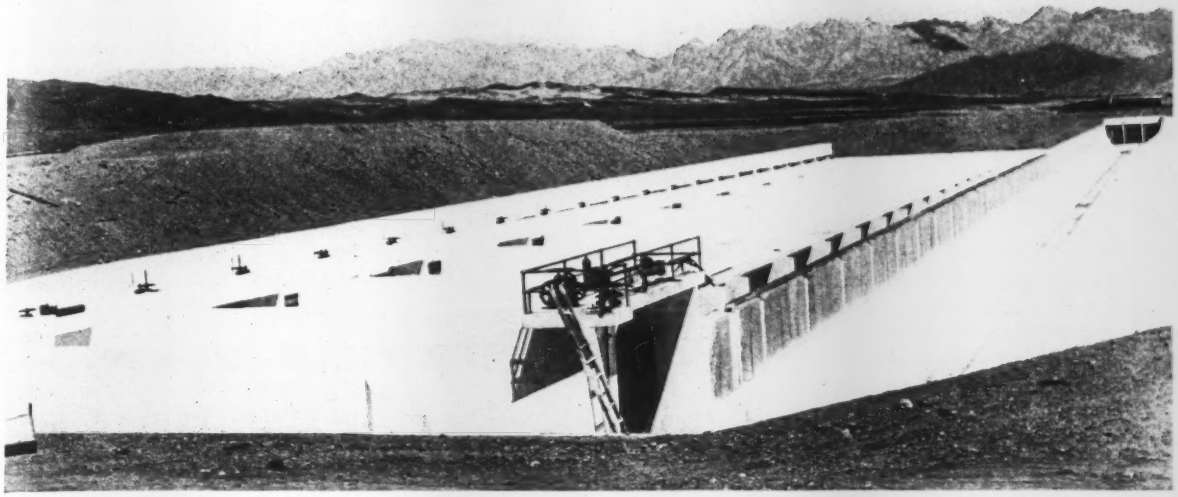


FIG. 1. TYPICAL SAND TRAP (EAGLE MOUNTAIN) WITH PERFORATED STEEL BAFFLES AT INLETS TO SAND TRAPS

Aqueduct Operating Program

L. V. BRANCH

Senior Engineer, Metropolitan Water District of Southern California

Silt removal, water softening and patrol of a long desert aqueduct were not obviated by a design that minimized operating requirements

Operating problems different from those met on the ordinary water system are expected by the Metropolitan Water District which will deliver water wholesale to member cities. Instead of dealing with meters, consumers' bills, etc., maintaining dependable and economical service in this case calls for: (1) synchronizing pumping plant operation to avoid unnecessary starting and stopping of pumps or wastage of water that may have been already lifted through two or three plants; (2) keeping up an aqueduct of great length, including 63 miles of open canal through desert terrain; and (3) maintaining communication facilities, including patrol roads, along 237 miles of transmission line, as well as along the aqueduct itself. A requirement of an entirely different sort will be: (4) reduction of the Colorado River water hardness to increase its suitability for domestic and industrial uses.

Operation of the aqueduct falls naturally into two divisions: (1) water diversion from the river at Parker reservoir, its elevation by five pumping plants, and its transportation through 242 miles of aqueduct to terminal storage at Cajalco reservoir, and (2) the delivery of water from Cajalco to meet varying needs of the member cities. This article is devoted to operation of the main aqueduct.

Storage along the aqueduct

Water delivery from the Colorado River to Cajalco reservoir will be, as a rule, at flows which are multiples of 200 sec.-ft., the rated capacity of each pumping unit. This will be made possible by using Cajalco's storage capacity (initial 100,000; ultimate 225,000 acre-ft.) to adjust the aqueduct flow to seasonal demands of member cities. This storage will also permit continuous delivery during shut downs of the aqueduct for maintenance and repairs. In operating estimates, shut downs 7 per cent of the time are anticipated.

At diversion rate of 200 sec.-ft., with no allowance for detention of water in reservoirs enroute, it will take 4½ to 5 days for water to reach Cajalco and about 2½ days more to flow from Cajalco to the westerly part of Los Angeles. Corresponding figures for full flow will be about 2½ days for the main aqueduct and 0.5 day for the distribution feeders.

Long, open canal sections of the aqueduct with maximum surface area, above Iron Mountain, Eagle Mountain and Hayfield pumping plants, furnish storage relatively large when compared to the discharge from the initial installation of three pumps in each plant. Under full flow conditions this canal storage will be effective during partial interruptions but will not prevent spilling in case of a complete sudden shut down of full capacity flow. Ample spillways are available for such emergencies.

At Iron Mountain and Eagle Mountain plants small reservoirs (100 and 112-acre-ft. capacity, respectively)

are provided (1) to store flows exceeding the capacity of pumps in operation and (2) to reduce water losses in event of partial or complete sudden shut-down of pumping facilities. Two pumps in each of these stations are so connected that they can be used for pumping direct from the reservoirs.

The discharge from Eagle Mountain pumps will flow in the aqueduct directly into the inlet pipes of the highest and most westerly pumping plant at Hayfield or it can be turned into the adjacent Hayfield reservoir (capacity 80,000 acre-ft.). From this point on the flow is through 116 mi. of gravity line to Cajalco reservoir.

Spillways

Flow from Copper Basin reservoir is remotely controlled, and conditions are such that with maximum height of water in the reservoir, faulty operation might result in overloading the aqueduct. Such overloading would do no harm in the Whipple tunnel, leading away from the reservoir, but might damage the conduit, siphon and canal sections below. To avoid such danger an overflow spillway is provided at Whipple tunnel outlet.

Four additional gate-controlled wasteways, combined with check gates in the aqueduct, will permit diversion of the full flow if need arises. There are combined wasteways and spillways at the Iron Mountain, Eagle Mountain and Hayfield plants. Further protection to open canal sections is provided by 23 small berm spillways that will discharge flows in excess of canal capacity.

Removal of river silt

Parker reservoir (capacity 716,000 acre-ft.) is expected to remove all silt that has come into the river below Boulder. Prior to construction of Boulder Dam the average silt load transported annually by the Colorado River past Topock, Ariz. (at the upper end of the Parker reservoir), is estimated to have been as much as 137,000 acre-ft.

Since the closure of Boulder Dam this silt flow has been reduced to a nominal amount. Thus the silt entering Parker reservoir will be chiefly that produced in the 10,730 sq. mi. tributary to the 155-mi. length of the river between Boulder and Parker dams, plus movement of silt previously deposited in the river between these structures.

TABLE I — COLORADO RIVER WATER CONTENTS BEFORE AND AFTER TREATMENT

Constituent	Raw Water (p.p.m.)	Treated Water (p.p.m.)
Total hardness	305.	125.
Carbonate hardness	145.	30.
Non-carbonate hardness	160.	95.
Silica (SiO_2)	19.	....
Iron	0.25	Less than 0.01
Calcium	81.	49.
Magnesium	25.	1.
Sodium } Potassium }	87.	118.
Bicarbonate (HCO_3)	182.	37.
Sulphate (SO_4)	243.	250.
Chloride	60.	60.
Nitrate (NO_3)	2.8	2.8
Total solids	609.	500.

TABLE II — WATER LOSSES IN TRANSIT

Type Conduit	Allowance for seepage loss (g.i.m.d.)†	Permitted by specifications (g.i.m.d.)	Actual tests (g.i.m.d.)
Welded steel pressure pipe	200	15	6.7
Precast concrete pipe	300	100	27
Dry grade tunnels and monolithic concrete conduit	500	300	121
Pressure tunnel and lined canal*	800	....	not tested
Monolithic concrete pressure conduit	1,000	....	not tested

† Gallons per inch of diameter per mile of line per day
* Based on conduit of equivalent wetted perimeter.

The only measurable quantity of stream flow entering the river in this area is the Bill Williams River which comes in from the Arizona side just above Parker Dam. This stream is flashy and has appreciable flows only after heavy rains when the silt content is high. Its average annual flow (10-yr. period) from a 5,300-sq. mi. basin is 102,000 acre-ft., and the estimated average silt yield is 1,800 acre-ft. This equals 0.34 acre-ft. of silt per square mile of the catchment area. It is probable that the flow of the Bill Williams River will be conserved for local use by construction of storage works. This anticipated development will very materially reduce the silt flow reaching Parker reservoir.

The total volume of silt that ultimately may be moved into Parker reservoir as a result of degrading the river bed below Boulder, will probably be 100,000 to 150,000 acre-ft. The lower figure is based on an average silt depth of 10 ft. for the 90 mi. of river between Mohave Valley and Boulder Dam; the larger figure is considered a safe maximum. These quantities plus the estimated annual average of 2,880 acre-ft. from tributary drainage will reduce Parker reservoir to half capacity in 70 to 90 yr. After degrading of the river bed has ceased only the silt from tributaries will remain and reservoir accumulation will be very slow.

Along the 63 mi. of open canal are considerable areas of light soils, blow sand and wind-blown materials that may lodge in the canal. Because of this, 27 depression-type sand traps, or pockets were put in the floor of open canal to trap the coarser bed load that otherwise would be deposited in the siphons, particularly when operated at part capacity. These depressions are 8½ ft. deep and 20 ft. square. Entrapped sand will be removed by a portable sand pumping device operated from the patrol road.

Larger sand traps, with settlement basins 70x420 ft. in size, are located just upstream from each of the three most westerly pumping plants. Here it is expected to catch any fine sand suspended in the water that has escaped the smaller traps.

Cleanout from these larger basins will be by a low head suction dredge pump on a gantry pumping into a concentration basin from which it will be removed and wasted by pumping or mechanical means. The size of these traps, which are arranged for easy enlargement, was based on observations of sand collected in completed sections of the canal and in water pans placed at critical points along the open canal.

Water quality

Colorado River water is and will probably always remain exceptionally free from bacterial contamination and industrial wastes. In the 180,000 sq. mi. water shed above Parker Dam, there is a population of about 315,000 (1.7 per sq. mi.).

Colorado River water has long been applied to domestic and irrigation uses with satisfactory results. By storing in Lake Mead relatively pure flood waters, formerly wasted into the ocean, the resultant river flow will have salinity and hardness reduced to less than half the former extremes.

The per cent of dissolved solids in the reservoir outflow is still comparatively high, however, due to easily eroded materials that make up large sections of the drainage basin. It always has been recognized that the water will require softening to be entirely satisfactory for the domestic and industrial uses of the metropolitan area. The average composition of Colorado River water before and after the proposed treatment is shown in Table I

Because of the large proportion of non-carbonate hardness, treatment with soda-ash as well as lime will be required to produce a satisfactorily softened water. Aside from design problems, to secure the most economical and efficient plant possible from an operating standpoint, special attention to sludge disposal will be necessary. Space for disposal of 100 acre-ft. of sludge per year during the first years of operation (700 acre-ft. per year ultimately) would be expensive in the highly developed suburban and citrus areas near Los Angeles. Special consideration is therefore being given to the development of treatment methods which will permit the reclamation of a large portion of the calcium content of the sludge. Recent experiments by the district staff at Boulder City indicates such recovery to be feasible and profitable. The saving in cost of lime more than offsets the cost of calcining the sludge, and the amount of the latter to be disposed of is reduced by at least two thirds. The treatment will not depart, essentially, from standard practice.

The preparation of preliminary plans and estimates for the treatment plant is under way but construction has not yet been authorized.

Delivery losses

In economic studies in connection with the design of the aqueduct, seepage losses were estimated at the values shown in Table II. Evaporation losses for canal and reservoirs in the desert were estimated at 6 ft. per year; at Cajalco and Morris reservoirs net evaporation losses were estimated at 3 ft. per year. Miscellaneous losses, including wasteway discharges, were expected to vary from 1 to 2 per cent of the total diversion.

Summing up these items, total losses are estimated at 16 per cent when the diversion is 200 sec.-ft. and at 10 per cent for flows of 500 sec.ft. or more.

Operating organization

Flow in the main aqueduct will be regulated at the five pumping plants. For actual operation of each plant, eight or nine men will be required with the initial installation of three pumps per plant. Gene pumping plant, near the intake, will be headquarters for the division superintendent in charge of pumping and his crew of assistants. This crew, which will do all testing, and maintenance of plant and camps, will total 16 to 18 men. An additional eight to ten men will be required for maintenance and operation of the Camino switching station and 237 mi. of 230-kv. transmission line.

Power generating units in the Boulder power plant furnishing power for district pumping will be operated under contract by the Los Angeles Bureau of Power and Light. Operation and maintenance of Parker Dam will be by the U. S. Bureau of Reclamation. Iron Mountain pumping plant, centrally located with reference to the 62.5 mi. of canal, will be headquarters for the crew assigned to patrol duty, maintenance of canal banks, patrol roads and fences, and removal of sand from sand traps. The 152 mi. of fencing installed around all open canal sections, wasteways, special structures and reservoirs will require some maintenance, but will greatly reduce the total amount of patroling and policing required of the maintenance forces.

As patrol roads on canal banks and construction roads along other sections of the aqueduct will permit patroling by automobile, the total force for operation and maintenance of the 242-mi. main aqueduct, will vary from 20 to 30 employees, exclusive of pumping plant operators.

In addition to a total operation and maintenance force of 100 to 120, a supervisory force of 70 to 75 for engineering, accounting and legal staffs will be required. A much greater force will be required in the construction of extensions, which will be undertaken later at intervals, as they are needed.

Fig. 2. The outlet tower at Cajalco reservoir is 121 ft. high (to operating floor). Fifty 30-in. gate valves deliver to a 14-ft. outlet tunnel.

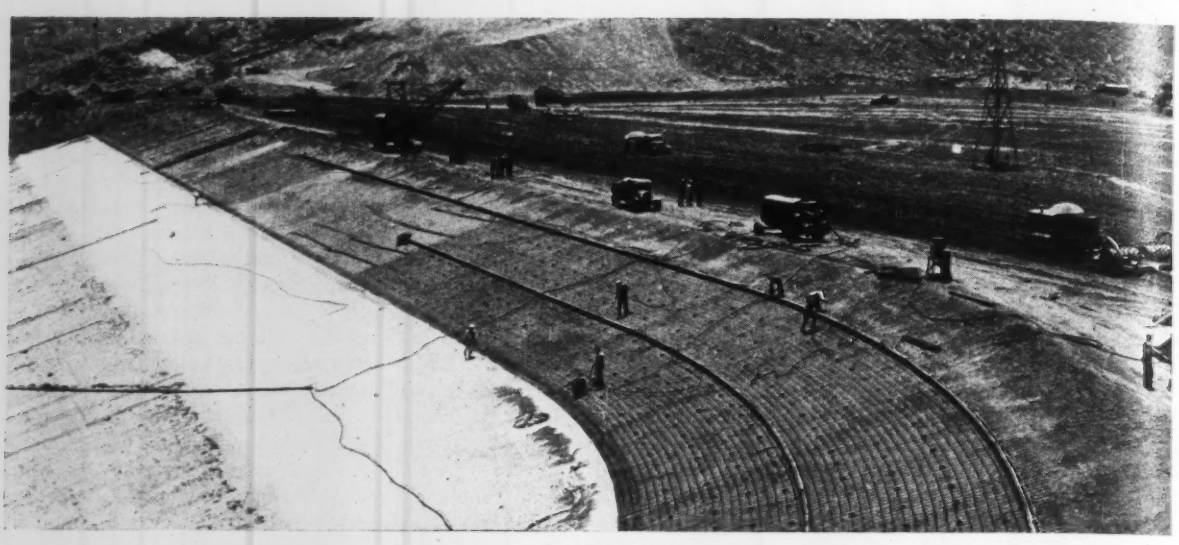


FIG. 1. PLACING REINFORCED CONCRETE PAVING ON THE SLOPE OF CAJALCO DAM

Wholesale Distribution to Member Cities

R. B. DIEMER

Distribution Engineer, Metropolitan Water District of Southern California

Heavy construction in thickly settled areas features program for several reservoirs and 250 mi. of large pipe and tunnels to be built in successive steps

AN ECONOMICAL DISTRIBUTION SYSTEM for the Colorado River Aqueduct called for something quite unlike the usual water distribution system for a large city. The main aqueduct terminates in Cajalco Reservoir so far to the east of coastal cities that about 250 mi. of large feeder mains ultimately will be required in the distribution system. Moreover, the district will not retail the supply, but will deliver in wholesale lots to member cities. Although the present population of member cities is about 2,000,000 the potential service area comprises most of the coastal plain of Southern California and there is no definite assurance as to just where future demand will be concentrated or what the rate of increase will be. Hence it was advisable, in early stages of development, to keep plans for later extensions as flexible as possible. This will be accomplished by building in progressive stages, beginning with initial development adequate for a few years and making additions as required. The unit construction plan is tentatively laid out, in a general way, up to the full aqueduct capacity of 1,500 sec.-ft.

Principal features of the initial distribution system are Cajalco reservoir, providing 100,000 acre-ft. of storage at the lower end of the main aqueduct; a single high line, known as the upper feeder, from Cajalco reservoir to upper areas of the district, with cross laterals to serve the lower areas, and Morris reservoir providing 38,000 acre-ft. of "close-in" storage on the upper feeder. The district has contracted to purchase Morris reservoir from Pasadena.

Regulation and control of flow in the feeder lines and protection against interruption of flow are to be effected at Cajalco and Morris reservoirs and at a few small operative reservoirs situated near the ends of the lines. All distribution lines will operate under pressure.

Many design and construction problems on the distribution system were different from any met on the main aqueduct. The aqueduct will deliver water at a fairly constant rate to one point, Cajalco reservoir; the distribution system on the other hand, will deliver at various destinations and at many different elevations. Numerous right-of-way and construction problems result from the high property values and the many interfering improvements in the areas which the distribution system traverses.

Cajalco reservoir

Cajalco was selected for storage at the end of the main aqueduct because (1) it is located at the upper end of the area served where the elevation permits of gravity delivery to all member cities, (2) it is on a stable granite formation at a safe distance from major fault zones and (3) the location is suitable for economical development in stages to a maximum capacity of about 225,000 acre-ft. The construction of the reservoir to the initial capacity of 100,000 acre-ft. was started in August 1935 and com-

pleted in February 1938. The work done under one general contract involved the excavation and lining of a diversion tunnel and outlet tunnel, the building of two earthfill embankments, namely, the main dam across Cajalco Creek and a dike on a low ridge along a portion of the northerly side of the reservoir, and the construction of a spillway and an outlet tower.

The diversion tunnel, used as a bypass for storm water in Cajalco Creek during the construction of the dam, is 9 ft. in diameter, 2,000 ft. long and is lined with concrete. The outlet tunnel with a capacity of 1,500 sec.-ft. is 14 ft. in diameter, 2,348 ft. long, and is lined with a welded steel membrane designed for full reservoir head. The membrane is backed by concrete and lined with 2 in. of shotcrete reinforced with welded steel mesh. Water will pass through this tunnel to the distribution system lines. Initially it connects the reservoir to the upper feeder; later it will supply all distribution lines west of Cajalco.

Water will leave the reservoir through a concrete outlet tower at the portal of the outlet tunnel. The tower is circular, has a 20-ft. inside diameter and is 145 ft. high. Fifty control valves were installed at ports on six different levels. These valves are the double disc type, 30 in. in diameter and are hydraulically operated.

Headworks for the distribution system, under construction near the downstream portal of the outlet tunnel, will regulate withdrawals from the reservoir into the upper feeder and into any future line west from Cajalco by means of valves and a forebay. Hydraulic head in the reservoir in excess of that required in the upper feeder will be dissipated at the headworks valves. While high water surface in the present reservoir is at El. 1,357, normal full flow hydraulic gradient in the upper feeder will range from El. 1,280 at the headworks to El. 940 at its western terminus near Eagle Rock.

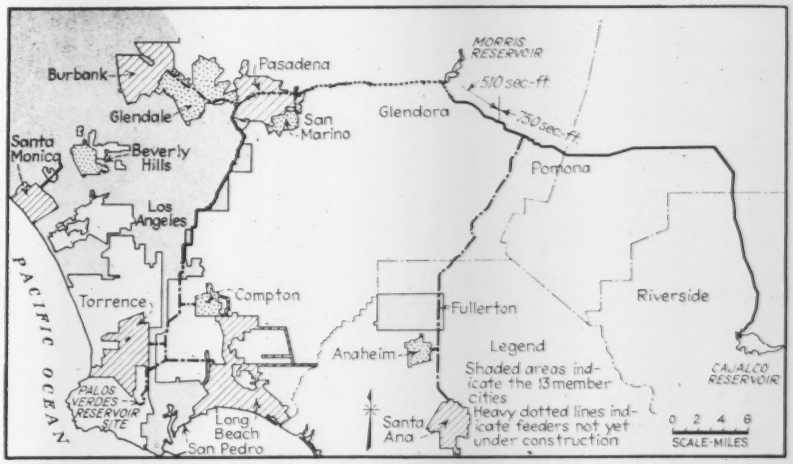


Fig. 2. About 250 miles of main feeder lines will be required to distribute aqueduct water to the cities of the coastal plane. Only feeders of the intial development are shown here.

Cajalco dam and dike were built with earthy materials thoroughly compacted to a high degree of density. Both have an 8-in. reinforced concrete paving on the upstream slope with a concrete cut-off wall to rock at the toe. Principal dimensions of the two structures are given in the following table.

TABLE I — PRINCIPAL DIMENSIONS OF CAJALCO EARTHFILLS

	Dam	Dike
Maximum height at axis (ft.)	210	94
Crest width (ft.)	50	32
Crest length (ft.)	2,170	7,575
Maximum width at base (ft.)	1,340	420
Embankment fill (cu. yd.)	3,175,000	3,857,000

Considerable preparatory work was required before the embankments were started involving mainly the removal of earth in the foundations which had less density than that of the completed fill. Advance explorations of fill material up to 40-ft. depths were made with 24-in. drill rigs and diamond core drills were used to prove adequacy of embankment foundations.

At the site of the dike, excavation was carried to a depth at which the material in place had a density and imperviousness equal to that which could be obtained in the compacted fill. The average depth of excavation was about 3 ft. Most of the excavated soil was redeposited and compacted in the fill.

Excavation in the dam foundation was carried down as much as 65 ft. in places because of low density and poor quality of rock for foundation purposes. Rocky material from the excavation was passed over grizzly bars 4 in. apart to remove small fragments. The coarse material was deposited in the pervious section at the toe of the dam and the fines were compacted in the rolled section.

Economy was effected by stockpiling and later using excavated materials whenever the quality was suitable for embankments. Proper utilization and disposition of excavated materials was important because all material from required excavations that could be used in the rolled fill decreased by just that much the amount of material that had to be imported at considerably higher unit costs.

Material for the embankments, other than that obtained from required excavations, was hauled ½ to 2½ mi. from borrow pits within the

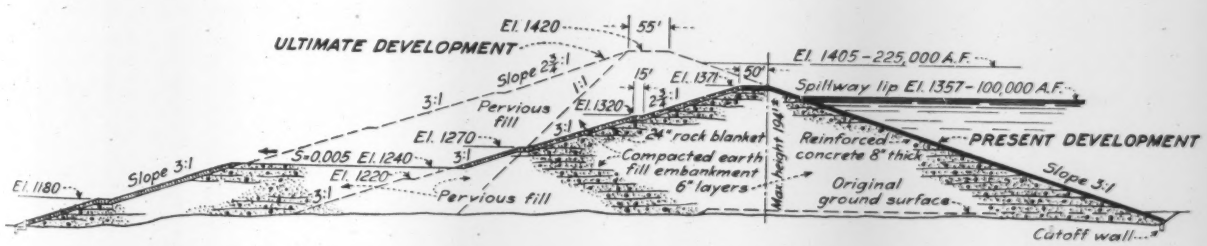


Fig. 3. Cross section of Cajalco Dam showing present and ultimate section.

reservoir area, using four 2½-cu. yd. shovels for excavating and loading the earth and a fleet of thirty 10-cu. yd. trucks for transportation. In general, the material was compacted in the embankments in 6-in. layers by tractor-drawn sheepsfoot rollers weighing 30,000 lb. About 16 trips were made over each 6-in. layer.

Density control

Materials in the borrowpits were all too dry in their natural condition to give the desired compaction in the embankment. Accordingly they were given approximately the desired moisture content prior to excavation by means of an overhead sprinkling system or by flooding small diked areas. After this wetting in place, any further moisture deficiency was made up by the use of hose during excavation or by sprinkler trucks on the embankment. The total amount of water used averaged 12 per cent by weight, and the average dry weight density of the compacted fills was about 125 lb. per cu. ft. Average density in the borrow pits was 105 to 110 lb. per cu. ft.

A well equipped soil testing laboratory maintained by the district at Cajalco carried on tests continuously during the construction period, and kept careful check on moisture, compaction, and percolation. The effectiveness of the compaction methods used shown by the small amount of settlement that has taken place in the fills; maximum settlements five months after completion were 0.10 ft. in the dike and 0.23 ft. in the dam.

Foundation grouting

To prevent leakage under the dam the foundation was grouted at the cut-off wall. Holes were drilled to depths of 30 to 200 ft. below the bottom of the wall at intervals of about 6 ft. and grout was forced in under pressure of 30 to 100 lb. per sq. in. Depth and spacing of the holes were made so as to assure an impervious curtain below the cut-off. The quantity of grout used averaged 0.20 cu. ft. per lineal ft. of drill hole.

A spillway and a concrete-lined overflow channel, with a capacity of 11,000 sec.-ft., were built near the north end of the dam. This spillway, together with 14 ft. of freeboard storage, should provide ample protection for the dam from any flood runoff that might develop in the 40 sq.mi. of drainage area tributary to the reservoir.

TABLE II — CONSTRUCTION TYPES ON UPPER FEEDER

Type	Inside diameters	Length (miles)
Welded steel pipe	9 ft. 8 in. to 11 ft. 6 in.	10.3
Precast concrete pipe	9 ft. 8 in. to 12 ft. 8 in.	35.7
Cast-in-place siphons	10 ft	0.3
Circular pressure tunnels	10 ft	15.7

A 62-mile feeder

The upper feeder has a capacity of 750 sec.-ft. from Cajalco to San Dimas, a takeout point for a future auxiliary line to the central portion of Los Angeles and intermediate areas; from San Dimas to Eagle Rock the capacity is 510 sec.-ft. Types of construction used on this 62-mile feeder which was built entirely by contract are given in Table II.

Most of the upper feeder, excepting tunnels, traverses thickly settled areas where right-of-way was expensive and numerous improvements were encountered. At several places it was less expensive to locate the line in streets instead of on private right-of-way despite the cost of restoring pavements and moving utility conduits. Where the line traversed private property, easements were preferred to fee purchase as a means of avoiding high severance damages. On easements the pipe was buried a minimum of 4 ft. below ground surface for protection against erosion and to permit use of the ground for agricultural purposes. easements through cultivated areas provided for the replacement of 3 ft. of top soil.

Steel pipe construction

Steel pipe was used on the upper feeder for 10.3 mi. across the Santa Ana River and adjacent low lying areas. Full flow head on this stretch will vary from 20 ft. at the highest point to 485 ft. at lowest level. Analyses prior to construction indicated that savings would be effected by building this part of the system as a single, full-sized line. The unusually large diameter and the high head on this pipe were not approved until extensive studies had shown that the proposed designs would be safe. The pipe was fabricated under contract in Los Angeles in lengths of 33 ft. 4 in.; thickness ranged from $\frac{17}{32}$ to $\frac{81}{32}$ in. All shop joints and seams were butt-welded electrically. (*ENR* May 20, 1937, p. 747.)

For protection against corrosion, the pipe was given a $\frac{3}{32}$-in. inside coating of coal-tar enamel and a ½-in. outside coating of gunite reinforced with wire mesh. In very corrosive soils, an outer coating of coal-tar enamel was put on before the gunite was applied. After the enameling, pipe sections were shipped by rail to a field plant, near the trench, where the gunite was applied and cured. This plan saved freight on the concrete coating.

Completed sections, weighing 25 to 36 tons, were hauled from the field yard to the trench on trucks constructed especially for this purpose. A heavy duty crane on crawlers traveling along the roadway beside the trench unloaded pipe sections from the trucks and placed them in the trench. All field joints were lap welded with portable electric welding equipment. After the enamel and gunite coatings were completed at the joints, the pipe was backfilled by sluicing and puddling with water jets. Average daily installation progress, using about twenty welding machines, was six pipe sections or 200 lin. ft.

Precast concrete pipe

Some parts of the upper feeder consist of precast concrete pipe of unprecedented size and length. This work was done by three contractors under a total of five contracts covering lengths of line from 4.5 to 11 mi. Some 9½ mi. of these pipes to be under heads of less than 75 ft. were provided with bell and spigot, mortar-type joints; on 26 mi. under heads up to 290 ft., lock-joint connections were used. Reinforcement was computed for a combination of external and internal loading. For heads less than 80 ft., a combination of circular and elliptical bar cages was used. For greater heads, a thin steel cylinder was added for water tightness and as a part of the reinforcement for internal pressures.

A complete plant for manufacturing and curing the concrete pipe was established at a convenient point by each contractor. Methods used at the three plants were similar; all precast concrete pipe was cast in 12-ft. sections and production varied from 12 to 16 sections per day, limited by the number of forms available. A notable factor in obtaining a dense concrete with a smooth surface in these pipes was a rotary steel rod, about 3

ft. longer than the form depth, revolved at about 500 r.p.m. while it was pushed down into the concrete along the face of the form.

Because the weight of these sections ranged from 26 to 43 tons, special equipment was developed both for transporting them to the trench and for lowering them into place. All trucks used for transportation were of the same general design, but the three contractors used different types of laying machines mainly because of different right-of-way conditions and size of pipe.

Equipment used to place the largest diameter pipe in open country east of Ontario consisted of a steam-operated stiff-leg derrick spanning the trench and traveling on a track of 48-ft. gage. For the 11-ft. 8-in. pipe through citrus groves and streets between Ontario and San Dimas an electrically operated truss type gantry was used which spanned the trench and traveled on track of 38-ft. gage. The smaller pipe west of San Dimas (10-ft. 3-in. and 9-ft. 8-in. diameter) was laid by a large crawler-type crane which traveled along one side of the trench.

All precast concrete pipe was bedded in a concrete cradle, poured soon after the laying of the pipe, to a height of one-sixth to one-half the diameter depending upon depth of backfill. Backfill was settled by a combination of puddling and flooding.

Normal laying progress varied from 12 to 16 sections (144 to 192 lin. ft.) per day depending upon production in the casting yard. In general this amount of pipe could be placed in the trench in an 8-hr. shift. The maximum number of sections placed in eight hours was 30—a progress record made when ample pipe sections were available.

After completion, all pipe lines were filled with water and tested for leakage under full operating heads. Specifications provided that leakage per inch of diameter per mile of line should not exceed 15 gal. per day for

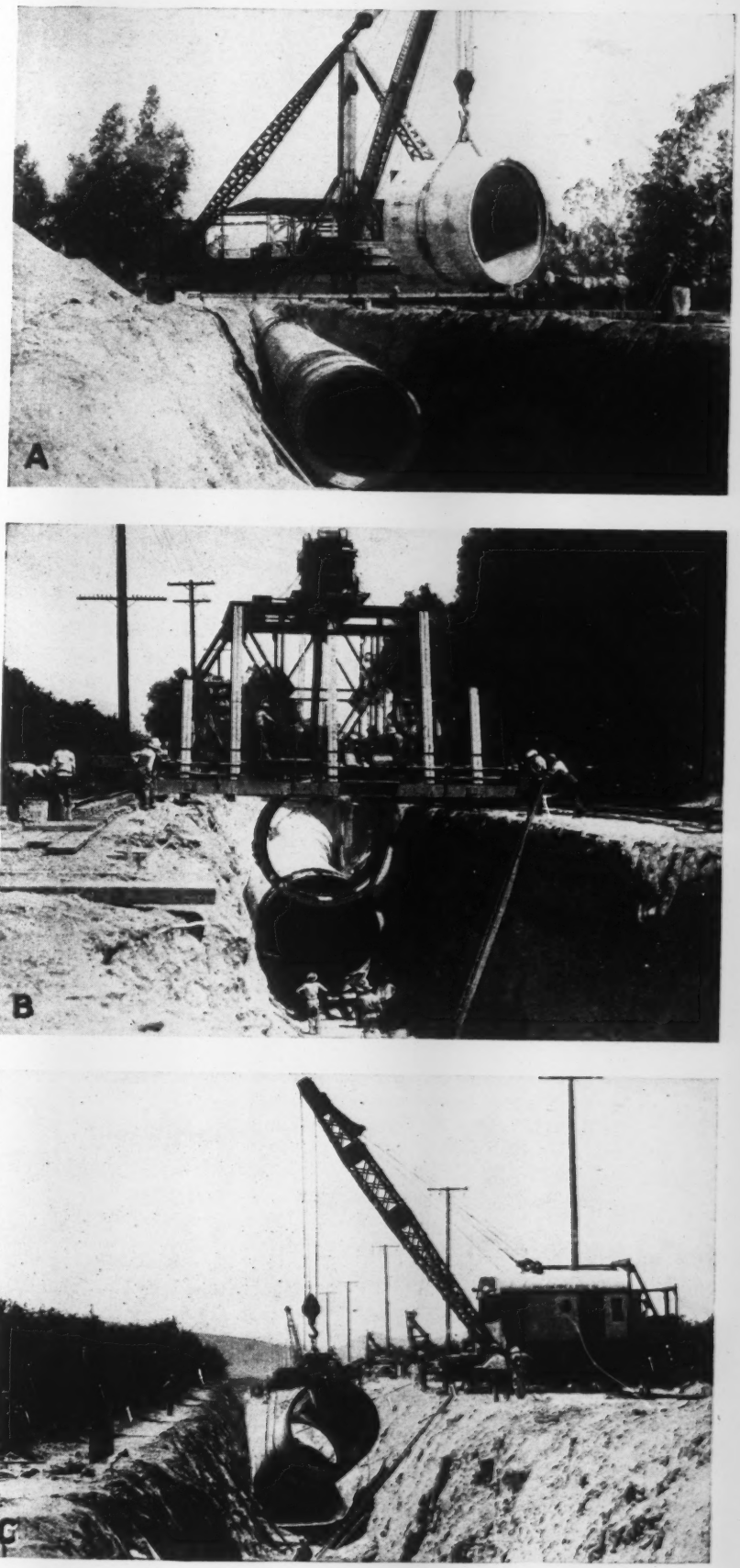


Fig. 4. **Three rigs were used for placing pipe in the trenches: (A) A steam operated gantry for placing the 43-ton precast concrete pipe; (B) An electric gantry for the 36-ton sections; and (C) An electric crane for the steel pipes.**

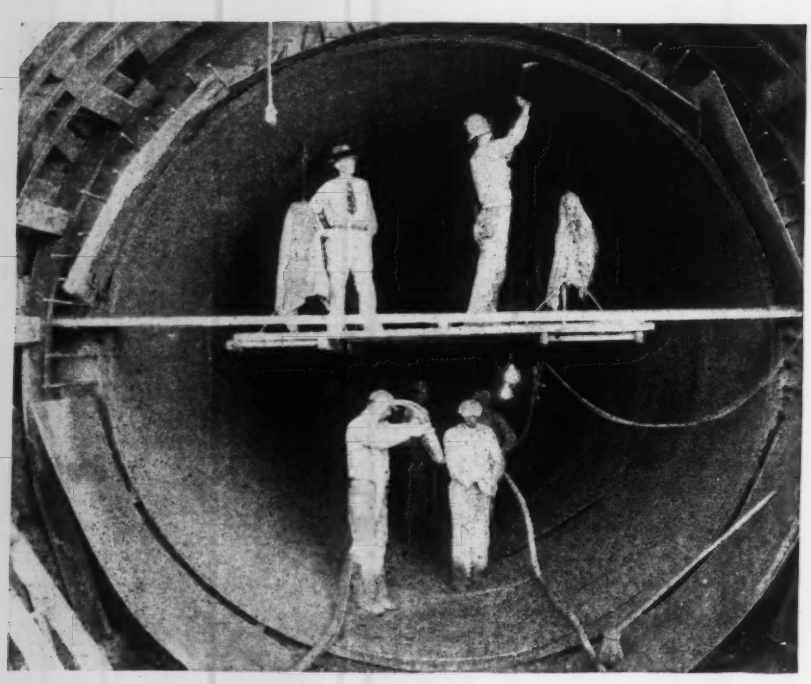


Fig. 4. Placing a 2-in. gunite lining on steel cylinders in Cajalco outlet tunnel. Note steel rib tunnel support and concrete lining back of steel cylinder.

the steel pipe and 100 gal. per day for the precast concrete pipe. Actual leakage, in all cases much less than allowable, averaged, respectively, 7 gal. and 27 gal. per in. of diameter per mile per day for the steel and the precast concrete lines.

Eight pressure tunnels

There are eight pressure tunnels on the upper feeder between Glendora and Glendale. These range in length from 0.2 to 6.1 mi., all are circular and are lined with concrete to a finished interior diameter of 10 ft. Six are through mountainous or hilly areas and the other two are under streets in residential sections of Sierra Madre and Pasadena. In these cities, tunnel construction was used for distances of 1.3 and 3.4 mi. respectively to avoid interference with urban improvements and traffic and the inconvenience to the public that would result from large open cuts in narrow city streets. These two tunnels are 30 to 70 ft. below the ground surface.

In both the Pasadena and Sierra Madre tunnels the ground encountered was partially cemented alluvium which was readily brought down by pneumatic spaders at the heading, without blasting. Supports consisted of steel bents, fabricated from 5-in. I-beams, backed with tight timber lagging on the sides and spiling in the roof. Average excavation progress per month was 1,470 ft. at Pasadena and 1.250 ft. at Sierra Madre. The greatest monthly progress was 2,185 ft. and best daily progress was 93 ft., both in the Pasadena tunnel.

Reinforced tunnel lining

The concrete lining of both tunnels was heavily reinforced to withstand full internal pressure resultant from heads up to 110 ft. The complete circular lining was placed, without longitudinal construction joints, in sections 60 to 80 ft. long between bulkheads. For this purpose special collapsible steel forms were designed, supported by traveling carrier. Concrete was delivered to the forms by pneumatic placer. As it was not possible to remove lagging and spiling in the alluvium prior to lining operations, due to danger of caving and runs, voids behind the lining were filled with grout.

Excavation in the other six tunnels was largely in rock of various degrees of hardness. Average excavation progress for all six was about 800 ft. per month per heading; the maximum was 1,210 ft.

Reinforcing steel was used in the lining of the rock tunnels where the depth of cover was less than twice the pressure head, or where the ground was soft and unstable. Heads on these tunnels range up to 260 ft. Under the maximum head a steel cylinder of $\frac{1}{4}$ to $\frac{7}{16}$ in. plates was used to increase strength and insure water tightness. This cylinder has 13 in. of concrete behind it, and is lined with 2 in. of gunite which protects steel and improves flow conditions.

Spillways are provided at drainage channels near points where the feeder is reduced in capacity. There is a spillway at the Puddingstone flood control channel near San Dimas, another is located on the westerly side of the Arroyo Seco, in Pasadena, and a third is contemplated in San Gabriel canyon on the connection to Morris reservoir.

Laterals to cities

Work is in progress on a contract covering the northerly 17.4 mi. of the Eagle Rock-Palos Verdes cross feeder which is to serve Los Angeles, Long Beach, Torrance, and Compton. It is located mainly in city streets below other utilities. The present contract provides for 55- and 51-in. welded steel pipe, with plate thickness of $\frac{3}{8}$ to $\frac{13}{32}$ in. Maximum head on the line will be about 450 ft.

The inside of this will have a $\frac{1}{2}$-in. cement mortar lining, centrifugally applied by spinning the pipe sections. An exterior gunite coating is used, with coal-tar enamel beneath it where corrosive soils or electrolytic conditions are bad. Special precautions are being taken to prevent electrolytic action as the result of numerous street railway and utility lines which the pipe will cross. In addition to insulating the pipe with concrete and coal-tar enamel, two insulating joints and several test connections are being put in.

Bids will be invited on other sections of the distribution system in the near future so that delivery to all thirteen member cities can begin as soon as the main aqueduct is completed. Included in the remaining work are a 13.5 mi. extension of the Eagle Rock-Palos Verdes cross feeder to reach the member cities in the Los Angeles harbor district, a 1,000-acre-ft. operative reservoir to be constructed in the Palos Verdes Hills at the end of the cross feeder, and laterals to other member cities.